**Addis Ababa University**

**Addis Ababa Institute of Technology**

**Energy Center**

**Master Thesis**

# Assessing Energy Potential and Generation of Electricity from Erta Ale Lava Lake in Ethiopia

A Thesis Submitted to Addis Ababa University, Addis Ababa Institute of Technology, Presented in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Energy Technology

By: *Mekonnen Ayane*

Advisor: *Dr.Ing. Wondwossen Bogale*

Co Advisor: *Professor Gezahegn Yirgu*

December, 2018

# Addis Ababa University

## Addis Ababa Institute of Technology

## Energy Center

## Master Thesis

# Assessing Energy Potential and Generation of Electricity from Erta Ale Lava Lake in Ethiopia

**Submitted by**

Mekonnen Ayane ________________ ________________
Name Signature Date

**Approved by Board of Examiners**

Dr. Ing. Wondwossen Bogale _________________ ______________
Advisor Signature Date

Professor Gezahegn Yirgu _________________ ______________
Co-Advisor Signature Date

Dr. Solomon Tesfamariam _________________ ______________
Internal examiner Signature Date

Dr. Ing. Abdulqadir Aman ________________ ________________
External examiner Signature Date

Dr. Ermias Tesfaye ________________ _______________
Director of Post Geraduate Signature Date

# Declaration

I, the undersigned, declare that this thesis entitled "***Assessing Energy Potential and Generation of Electricity from Erta Ale Lava Lake in Ethiopia***" is my original work under Energy Center, AAiT, and has not been submitted by any other person for an award of a degree in this or any other University, and that all resources of materials used for this thesis have been duly acknowledged and a list of references is given.

**Name:**

Mekonnen Ayane Fayissa ________________________

Signature

This thesis has been submitted to the Addis Ababa University with my approval as the University Advisor and Co-Advisor.

**Advisor:**

Dr. Ing. Wondwossen Bogale ________________________

Signature

**Co-Advisor:**

Professor Gezahegn Yirgu ________________________

Signature

# Abstract

Ethiopia is a developing country, where majority of the population lives in rural areas. In 2016, only 26.56 % of Ethiopian inhabitants have an access to electricity, as reported by World Bank, which could be considered as one of the lowest rates of access to modern energy services, in which biomass primarily shares 92.4% of total energy supply.

This project Focus on Assessing Energy Potential and Generation of Electricity from Erta Ale Lava Lake in Ethiopia. The main objective of this project is to design, analysis and optimization of a special type power plant by changing shape, orientation and principle of operation of the steam generator using Lava Lake as a source of energy. Estimation of three dimensional temperature distributions using linear interpolation and energy potential of Erta Ale Lava Lake using shell discretization method as well as estimation of maximum possible extracted power using optimization method has been calculated. Many impossibilities were made possible by developing new mechanisms. After this, a brick coated steam boiler which safely operates at a high temperature up to 1200 $^{o}$C have been designed, analyzed, optimized.

Average temperature of the lava lake estimated to 1200 $^{o}$C and the lava lake would be estimated to continuously join with mantle and core of the Earth through Magma tube and Magma reservoir. An internal heat content of our Planet was estimated to be $10^{31}$ Joules ($3x10^{15}$ TWH), which is approximately 100 billion times current (2016) total annual energy consumption of the world. An ideal power potential of this lava lake estimated to 408 MW and maximum extractable power estimated to be 200 MW which could be estimated to 1.7 billion birr per annum. Maximum possible length of boiler pipes, number of boiler pipes, space between them and diameter of the pipe has been estimated to be 1500 m, 93 m and 600 mm respectively.

This special type power plant mainly consists of brick coated steam generator, cooling tower, pump, reheater, regenerator and other accessories. In general, this extra ordinary energy extraction from Lava Lake is environmentally friendly and easy to control.

***Key words:*** *energy, electricity, Erta Ale, Lava Lake, interpolation, optimization.*

## Acknowledgement

First of all, I would like to express my heartfelt thanks to my advisor Dr. Ing. Wondwossen Bogale, who had supplied me; valuable comments, professional guidance, meaningful support and motivation from the very beginning to the end. His academic potential, responsibility, creativity, kindness, versatility, trustworthiness, patience, systematic problem solving techniques and professional life style would help me to share a new professional life style in general. I would also like to thank in advance my co advisor Professor Gezahegn Yirgu, who have supplied me; useful advice, especially, on geological back ground, properties, and temperature distribution as well as sharing me deep experience on Erta ale lava lake.

I would also like to thank Mr. Fitsum Salehu who had supported me on the beginning of my work. I would also not like to jump over the great suggestion, advice and facilitation of the energy center head Dr. Solomon Tesfamariam.  I would also like to recognize Mr. Tewodros Walle, Energy center staff and my close friends Wubishet Degife and Feyissa Bekele, who have interfered directly or indirectly in my project. The contribution of all my previous instructors, who have supplied me the permanent knowledge during the course work, in my specialization is undiminished.

Finally, I would like to recognize Wollo University, Kombolcha institute of Technology, for sponsoring my MSc studies in Energy Technology at Addis Ababa University, Institute of Technology.

## Table of Contents

## List of Figures

## List of Tables

## List of Abbreviations

| | |
|---|---|
| PMM II | Perpetual motion machine two |
| MHD | Magneto hydro dynamic generator |
| IDDP | Iceland deep drilling project |
| TWH | Terra Watt hour |
| IC engine | Internal combustion engine |
| TS diagram | Temperature entropy diagram |
| OFWH | Open feed water heater |
| CFWH | Closed feed water heater |
| 3D | Three dimensional |
| EEPCO | Ethiopian Electric Power Corporation Organization |
| MW | Mega Watt |
| LMTD | Log Mean Temperature Difference |

## List of Nomenclature

| | |
|---|---|
| $q_{out}$ | heat rejected by condenser |
| $q_{in}$ | heat added to boiler |
| $w_{pump\ in}$ | input work of pump |
| $w_{turbine\ out}$ | output work of turbine |
| $\eta_{th}$ | thermal efficiency |
| $w_{net}$ | net output work |
| $Q_{total}$ | total heat content of the earth |
| $Q_{p.u.d}$ | heat content per unit depth of the lake |
| $C_{pl}$ | specific heat capacity of lava |
| $R_t$ | total thermal resistance |
| $L_1$ | thickness of steel pipe |
| $L_2$ | thickness of brick |
| $h_1$ | convective heat transfer coefficient of lava |
| $h_2$ | convective heat transfer coefficient of steam |
| $q_x'$ | heat transfer per unit area |
| $q_x$ | heat transfer per unit depth |
| $T_{s,1}$ | temperature at outer surface of brick |
| $T_{s,2}$ | temperature at outer surface of steel pipe |
| $T_{s,3}$ | temperature at inner surface of steel pipe |
| $T_{\infty,1}$ | temperature of lava |
| $T_{\infty,2}$ | temperature of steam |
| $L$ | depth of insertion of pipe |
| $F_{bouyant}$ | buoyant force |
| $m_{ore}$ | mass of ore |
| $m_{steel}$ | mass of steel |
| $P_{out}$ | pressure outside steel boiler |
| $P_{in}$ | pressure inside steel boiler |
| $C_{steel}$ | cost of steel |
| $C_{ore}$ | cost of ore |

| | |
|---|---|
| $N_{pt}$ | total number of pipes |
| $P_s$ | power per single boiler pipe |
| $P_t$ | total power from the lake |
| $Q_{boiler}$ | heat transfer to boiler |
| $T_{sat}$ | saturation temperature |
| $\eta_{pump}$ | pump efficiency |
| $\eta_{turbine}$ | turbine efficiency |
| $P_f$ | saturated liquid water pressure |
| $m_s$ | mass flow rate of steam |
| $P_{net}$ | net power output |
| $P_{single}$ | power per one boiler |
| $V_s$ | speed of steam in boiler |
| $m_{sp}$ | mass flow rate of steam per one pipe |
| $V_{st}$ | volume flow rate of steam per one pipe |
| $N_d$ | number of down comers |
| $m_{wmakeup}$ | mass flow rate of make-up water |
| $V_{flowair}$ | volume flow rate of air |
| $P_f$ | Fan power |
| $m_w$ | mass flow rate of water |
| $m_a$ | mass flow rate of air |

# Chapter one

## 1) Introduction

### 1.1) Background of the Study

Energy is the most essential requirement than ever for all living things everywhere in a universe until the end of time. It is a property that transferred to or from an object in different form. The two laws of nature, which is always true everywhere in a universe states that energy is neither created nor destroyed and actual energy transfer process can take place in one direction.

By using temperature measurements from more than 20,000 boreholes around the world, Geologists have estimated that 44 terawatts (44 trillion watts) of heat energy continually flow into space from earth's interior, which could be approximately 7 times current (2014) worldwide power consumption [1]. There could be a question, where does it come from? Due to energy on the loose by gravitational downfall, the earth initially heated up. But, based on the age of the earth 4.6 billion years, this heat energy would have been completely run out off.

However, as we observe from our planet, the volcanic activity shows that, the core of the earth is still hot. This energy which cause core of the earth hot is produced by the primordial heat, which is heritage of heat from the formation of the Earth and this was continuously replenished at a rate of 30 TW by radioactive decay of minerals. Early in earth's history, heavy radioactive elements such as uranium along with Nickel and Iron descended to the earth's core. By the principle of nuclear fission reaction of those elements, the core of the earth is kept hot [2].

An internal heat content of Our Planet was estimated to be $10^{31}$ joules ($3x10^{15}$ TWH), which is approximately 100 billion times current (2016) total annual energy consumption of the world [3]. This could be approximately 100 trillion times current Ethiopian annual energy consumption. It is obvious that this amount is extremely larger than that of energy content of all world fossil fuel and energy content of all world nuclear fission fuel which could be completely run out of within the matter of around 200 and 60 years respectively.

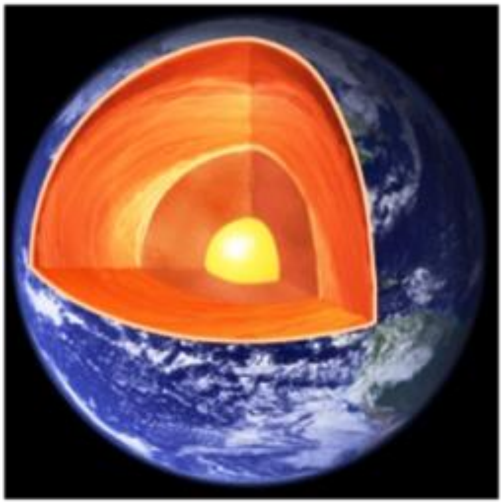


**Figure 1.1 Internal structure of the earth [2]**

There were unlimited numbers of attempt in science to obtain useful form of energy, most of the time electrical energy, from different energy resources. Using unalterable scientific laws, capturing direct solar energy through collectors, capturing wind energy using turbines, converting fuels energy using IC engine as well as power plants, converting fluid energy using hydraulic turbines , using nuclear power plants, using geothermal plants and etc. There was also unlimited number of attempts to close efficiency of those devices to perpetual motion machines PMM II.

Sources of most of useful energy throughout the world is heat energy obtained from fossil fuels which is a limited resource through common energy conversion devices using basic thermodynamic cycles such as rankine, otto and diesel cycles. But the main challenge is a limited thermal efficiency which is limited to maximum of from 35% to 40%.

Unlike an ordinary available energy conversion system and devices, this system is generation of electricity from high temperature continuously flowing lava lake. Erta Ale Lave Lake has a very large thermal energy potential which is estimated in this thesis through scientific procedure and optimization. This could support national electricity supply and balance demand and supply of the country.

## 1.2) Statement of the problem

In 2016, only 26.56 % of Ethiopian inhabitants have an access to electricity, by World Bank report, which could be considered as one of the lowest rates of access to modern energy services, in which biomass primarily shares 92.4% of total energy supply. But, the country is gifted with generous renewable energy resources such as hydropower, geothermal, solar, wind energy, geothermal energy resources, etc. [24].

It is very difficult to directly capture thermal energy from Erta Ale Lava Lake, which its temperature reaches up to 1200 $^0$C, which is strong enough to fail operating performance of the boiler and turbine materials. It is also very difficult to design special boiler material which operates properly at this maximum temperature. The height of the lake reaches up to 80 meter which challenges the installation of different of pipes [11]. The exact depth and volume of the lake is unknown. Due to this reason, calculation of the exact energy potential of this lake is difficult.

Basic research questions include both theoretical and technical questions as follows.

**Theoretical questions**

- Why plenty of energy potential did not extracted from erta ale Lava Lake in Ethiopia?
- Is there any other place like this which has Lava Lake in the world?
- Is there any attempt to extract energy from Lava Lake throughout the world? Why?
- What is the difference between extraction of energy from geothermal and lava lake? Which is more efficient?
- Is it possible to extract useful energy from Erta Ale Lava Lake?

**Technical questions**

Based on the following technical and specific questions specific objective of the study will be stated.

- What are three dimensional temperature distribution and profile of Erta Ale Lava Lake look like through the volume of the lake?
- What is ideal energy potential of the lake?
- What is the maximum amount of power in MW that will be extracted from this lava lake without condensation of the Lava?
- Is it possible to design steam generator which operates at high temperature up to 1,200 $^o$C? How?

- How maximum possible length of boiler did pipes, space between them and heat exchanger contact area without any damage was optimized?
- What type of down comer keep temperature below boiling point of lava?
- What are basic constraints which disallow this energy potential to fully extract?

## 1.3) Objective

### 1.3.1) Main Objective

The main objective of this project is assessing maximum possible extractable power and design, analysis and optimization of special type power plant to generate electricity from Erta Ale Lava Lake in Ethiopia.

### 1.3.2) Specific Objectives

- To estimate three dimensional temperature distribution of Erta Ale lava lake with the highest possible accuracy.
- To estimate ideal energy potential of the lake.
- To estimate the highest possible extractable power from this lava lake without condensation of the Lava.
- To design brick coated steam generator which operates at a temperature up to 1,200 $^{o}$C.
- To design maximum possible length of boiler pipes, space between them and heat exchanger contact area without any damage.
- To design special type down comer which keep temperature above melting point of lava.
- To identify some basic constraints which disallow this energy potential to fully extract.

## 1.4) Significance of the study

- It will add knowledge base on generating power from Lava Lake and its technology.
- It will suggest the possibility of generation of power from erta ale Lava Lake in a reality.
- It will used to recommend further study on steam boiler design.

## 1.5) Scope of the study

Overall power plant design is very broad fields which require more sophisticated design software and bulk data collections as well as a wide group knowledge rather than single individual knowledge. There are also wide categories of power plants and their principles in different parts of the world. But power plant in this project is mainly focuses on the consideration of Ethiopian Erta Ale Lava Lake as a source of energy. Even though some of its parts are similar to that of conventional power plant, its orientation of steam generator is totally different from conventional rankine cycle operated power plant.

So, in this project due to constraints such as budget, time, lack of deep knowledge about full design of complicated power plant which operates in a reality, which need a group of designers other than individual, this work is limited to estimation of energy potential using previously collected temperature data by different researchers and focusing on specific design of brick coated steam generator. To simplify and optimize the whole activities in a project, instead of detail design of each components such as turbine blade thickness and detail dimensions of complicated plant components, the study identify specification and select commonly manufactured components. The research focuses on calculation, interpolation, discretization and optimization of thermodynamic properties such as energy, power, steam character, boiler parameters, etc.

Simulation of many conventional power plants have been easily done by Thermo Flex Software and other commonly used Software. But, in this project, components and principle of operation as well as source of energy is totally different and it is not possible to properly and easily simulate by those common Softwares. So, it require to develop a new Software for simulation of this system. But, developing a new Software is very difficult and time consuming for this work.

## 1.6) Methodology

In order to realize all specific objectives of the study and answer technical questions raised in this study, the following scientific and procedural steps has been done through unique creative perspective point of view. It is also very important to consider theoretical questions and try to assume characteristics of the lava lake.

- **Primary data collection:** it is very difficult to directly measures and observes thermodynamic properties of the lake such as temperature, pressure, density, specific heat capacity, melting point, etc. It is very important to observe and assume some basic design facts about the lake such as geological background as well as scenario of this Erta Ale Lava Lake, through an interview with an experienced scholars who had done many journals on the lake.
- **Secondary data collection:** to fully understand and assume general characteristics of the lake and basic principle of generation of energy, it is very important to review different literatures such as

text books, journals, newspapers, etc. Some thermodynamic properties of the lake that was tried to study by many scholars such as: temperature distribution on the surface of the lake, with maximum temperature up to 1200 $^{o}$C, as it was active for the last 100 years, the area of the lake, its surface location from crater rim, specific heat capacity, thermal diffusivity, sensible and radiative heat flux, crystallization, latent heat of basalt, basalt density, estimate volume of lave erupted in 2010, etc has used.

- **Linear interpolation technique:** To estimate temperature distribution of the lake, linear interpolation method using observed temperature at the surface of the lake and maximum recorded temperature at the interior of the earth due to pressure difference through the depth of the earth has used.
- **Shell discretization method:** To estimate the highest possible extractable power from this lava lake without condensation of the Lava, three dimensional temperature distribution that had already obtained by linear interpolation and specific heat capacity of lava as well as the volume of the earth has used. Then, assuming average density of lava, energy potential by Excel, using shell discretization technique has been calculated.
- **Mathematical modeling techniques:** To design brick coated steam generator which operates at a temperature up to 1,200 $^{o}$C, convective and conductive heat transfer analysis of heat exchanger has been used. I have fixed maximum and minimum temperatures outside and inside the steel pipe has been fixed. Then it possible to calculate thickness of steal and brick respectively for safe operation.
- **Optimization technique:** To design maximum possible length of boiler pipes, space between them and heat exchanger contact area without any damage, optimization based on material property, material cost, and any thermo dynamic as well as heat transfer constraints that affect the amount power to be extracted Excel has been used. Solidification of lava and its effect on heat exchanger has also been considered. By optimizing all thermodynamic properties and all sizes of components, overall power produced by this power plant has been estimated. Buoyancy effect and its solution, solidification effect and its solution, installation problem and its solution, condensation problem and its solution, falling crystal effect and its solution, etc. has been considered. Shape, orientation and principle of operation shall be new to install this new power plant with the highest possible efficiency and extracted power.

## 1.7) Outline of the thesis

This thesis paper includes six chapters. The first chapter is the introduction part that that is mainly focus on the background, statement of the problem, objectives of the study, Significance of the study, Scope of the study and Methodology.

Chapter two is a literature review in which different related and basic works are discussed. Some basic information's of the Lake are briefly discussed in this chapter. In addition, some useful related attempts throughout the world has been tried to be observed. Principle of operations of conventional steam power plants are also discussed. The research gap has identified in this chapter.

Chapter three is about general characteristics of Erta Ale Lava Lake that directly related to estimation of energy potential and generation of electricity. Geological background and temperature measurement of Erta Ale Lava Lake are briefly discussed in this chapter. Overview of internal structure of the Earth, magma tube and magma reservoir was given attention.

In addition, general overview of energy and the end of universe, Ethiopian energy option and Erta Ale Lava Lake as well as general overview of electricity generation from Erta Ale Lava Lake are also discussed.

Chapter four tells about temperature distribution and estimation of total energy content of the lake. Continuity of the lake and its scenario is also presented in this chapter.

Chapters five is mainly focus on power potential of the lake. Special type steam generator is designed by solving different extra ordinary impracticalities in this chapter. Power potential per unit depth was discussed and maximum depth of installation was discussed. Diameter of pipe, the gap between each pipe and length of the pipes are optimized by passing through a number of constraints. Brick coated steam boiler are designed to control temperature at each surface of steel pipe. Any problems related to temperature and buoyancy effect are also included in this chapter. Finally, maximum possible extractable power from the lake was estimated after optimization of different parameters.

Chapter six is about Conclusion and Recommendation. Conclusions that have been derived from this research work followed by recommendations for further study.

# Chapter Two

## 2) Review of related literature

### 2.1) Introduction

Most of power plants were characterized by generation electricity using heat energy, either coal plant or geothermal plant, using almost similar principle of operation and main thermodynamic cycles as well as main devices like boiler, pump, condenser and turbine. Shape, orientation and principle of operation of Erta Ale Lave Lake plant is different. In this chapter, as the main task of this project is separately assessing energy potential and plant design for generation of electricity, different methods related to this two main activities will be discussed. The first task is searching direct related works or attempts which will add knowledge base on this project. The second task is discussing the design procedure of different types and parts of power plants.

### 2.2) Evolution of power plants

Heat energy is converted to electric energy in thermal power station. Water is heated and turns into steam and spins a steam turbine which drives an electrical generator. After it passes through the turbine, the steam is condensed in a condenser and recycled to where it was heated. This is known as a Rankine cycle.

In 1768, James Watt initially developed reciprocating steam engine which used to produce mechanical power with notable improvements. When the first commercially developed central electrical power stations were established in 1882, at Holborn Viaduct power station in London and Pearl Street Station in New York, reciprocating steam engines were used. In 1884, development of the steam turbine provided larger and more efficient machine designs for central generating stations. By 1892, the turbine was considered a better alternative to reciprocating engines offered higher speeds, more compact machinery, and stable speed regulation allowing for parallel synchronous operation of generators on a common bus. The energy efficiency of a conventional thermal power station, can be considered as profitable energy produced as a percent of the heating value of the fuel consumed, is typically 33% to 48% [29].

The energy of a thermal power station that was not utilized in power production must leave the plant in the form of heat to the environment. This waste heat can go through a condenser and be disposed of with cooling water or in cooling towers.

The direct cost of electric energy produced by a thermal power station is the result of cost of fuel, capital cost for the plant, operator labor cost, maintenance, and such factors as ash handling and disposal. The feed water cycle begins with condensate water being pumped out of the condenser after traveling through the steam turbines. The condenser tubes are made of brass or stainless steel to resist corrosion from either side. Nonetheless, they may become internally spoiled during operation by bacteria or algae in the cooling water or by mineral scaling, all of which inhibit heat transfer and reduce thermodynamic efficiency. Many plants include an automatic cleaning system that circulates sponge rubber balls through the tubes to scrub them without the need to take the system off-line [29].

## 2.3) Conventional steam Power Plants

### 2.3.1) Introduction

A thermal power plant is a power plant where steam is used to drive a steam turbine. This turbine is connected to an electrical generator. After this, the water is condensed, and may be used again. This is known as the Rankine cycle. There are different procedures that can be used to heat the water; this gives different types of thermal power plants.

Electrical energy is the only form of energy that is easy to produce, transport and control. The main sources of energy for power plants are using Fossil Fuels (Coal, Natural Gas, Oil, etc.), Nuclear Fuels (Plutonium, Uranium 235, etc.)' Geothermal energy (underground steam), Hydropower plants etc. power plant system is the same for both, except for the way the input energy is used.

Water is the most important and determinant working medium because of its low cost, availability and high enthalpy of vaporization. The phase changing character of this abundant fluid make it suitable for power generation purpose. Ideal gas is also one of the most common working medium especially in transportation energy conversion devices due to its availability everywhere in our planet and its low density. But this project mainly focus on closed system or control volume analysis due to scarcity water at the site. Water is also the most common working fluid in a condenser or wet cooling tower of the plant.

The ideal Rankine cycle does not involve any internal irreversibility's and consists of the following four processes:

- ***(Process 1-2),*** Isentropic compression in a pump.
- ***(Process 2-3),*** Constant pressure heat addition in a boiler.
- ***(Process 3-4),*** Isentropic expansion in a turbine.
- ***(Process 4-1),*** Constant pressure heat rejection in a condenser.

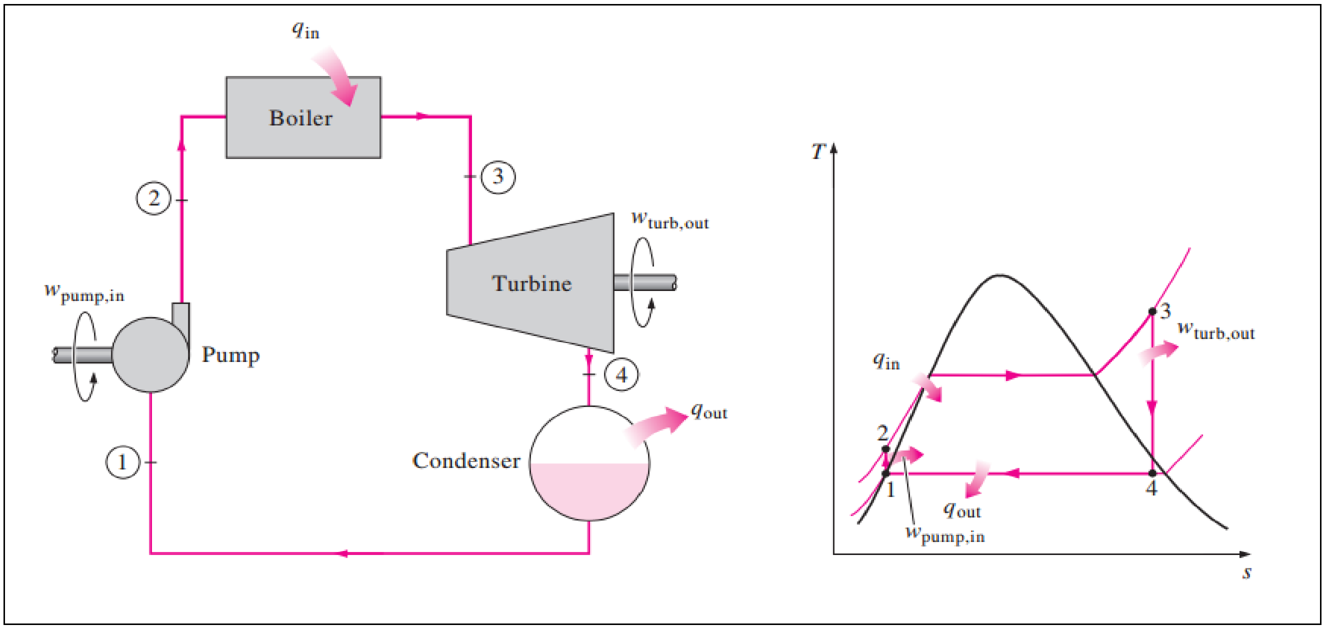


**Figure 2.1. The simple ideal rankine cycle [19].**

### Energy Analysis of the Ideal Rankine Cycle

All four components associated with the Rankine cycle (the pump, boiler, turbine, and condenser) are steady-flow devices, and thus all four processes that make up the Rankine cycle can be analyzed as steady-flow processes. The kinetic and potential energy changes of the steam are usually small relative to the work and heat transfer terms and are therefore usually neglected. Then the steady-flow energy equation per unit mass of steam reduces to:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i \quad \text{(kJ/kg)} \ldots\ldots \quad (2.1)$$

The boiler and the condenser do not involve any work, and the pump and the turbine are assumed to be isentropic. Then the conservation of energy relation for each device can be expressed as follows:

Pump (q = 0): $W_{pump\ in} = h_3 - h_2$ or $W_{pump\ in} = v\ (p_2 - p_1)$………….... (2.2)

Boiler (w = 0): $q_{in} = h_3 - h_2$ ……………………………………………...….. (2.3)

Turbine (q = 0): $w_{turbine\ out} = h_3 - h_4$ ………………………..……………... (2.4)

Condenser (w = 0): $q_{out} = h_4 - h_1$ ……………………………………..… (2.5)

Thermal efficiency of rankine cycle become:

$\eta_{th} = w_{net} / q_{in} = 1 - q_{out}/q_{in}$ and $w_{net} = q_{in} - q_{out} = w_{turbine\ out} - w_{pump\ in}$ ….(2.6)

Common sources of irreversibility in this cycle are fluid friction, which cause pressure drop or need greater pump work, and heat loss, which cause increase more heat transfer in boiler.

## 2.3.2) General characteristics conventional steam power plants

To achieve higher thermal efficiency, increase average temperature at which heat is added or decrease average temperature at which heat is rejected. That is, average fluid temperature should be as high as possible during heat addition and as low as possible during heat rejection [19].

### Lowering the Condenser Pressure

Lowering the operating pressure of the condenser automatically lowers the temperature of the steam, and thus the temperature at which heat is rejected.

- Lowering Condenser pressure lower temperature at which heat is rejected and this intern increase the area under curve of T-S diagram.
- However, in most power plants, limiting value of condenser pressure is 0.08 bar. Below this pressure there is a tremendous air leakage increases and as air is insulator, so condenser do not condense properly.
- Even though, remove air by some mechanism, it is not possible to reduce condenser pressure less than 0.08 bar, longer turbine blade not overcome larger speed. Because centrifugal force increase as radius of the blade increase.
- Condenser pressure cannot lower than saturation pressure corresponding to temperature of cooling medium most of the time more than room temperature.

- The criteria for the end state of steam after expansion is that x = 0.88 (12 % moisture) because high speed moisture damage turbine blade. But, in general, this could be corrected by super heating steam.

### Superheating the Steam

The average temperature at which heat is transferred to steam can be increased without increasing the boiler pressure by superheating the steam to high temperatures.

- It decreases moisture content leaving the turbine (satisfying the criteria for the end state of steam after expansion, that x = 0.88 (12 % moisture)
- This is an advantage without increasing boiler pressure.
- However, temperature heat is added is limited to 568 $^{o}$C due to metallurgical property.
- But, scientists are trying to use Ruthenium Mono Crystal which withstand up to 1100 $^{o}$C.

### Increasing the Boiler Pressure

Another way of increasing the average temperature during the heat-addition process is to increase the operating pressure of the boiler, which automatically raises the temperature at which boiling takes place.

- This is an advantage to increase average temperature to increase area under the curve.
- But, moisture content increase at turbine exit (this shall be corrected).
- But, always increase output may not necessarily increase efficiency, because there is also decrease net output work in this case.
- Maximum pressure is limited to 180 bar. Because it is difficult to design pipes.
- But, super critical boilers operates at 374 $^{o}$C and 225 bar. It is large and robust.

### The ideal reheat cycle

There were two possibilities to take advantage of the increased efficiencies at higher boiler pressures without facing the problem of excessive moisture at the final stages of the turbine.

The first one is superheat the steam to very high temperatures before it enters the turbine. This would be the desirable solution since the average temperature at which heat is added would also increase, thus increasing the cycle efficiency. This is not a viable solution, however, since it requires raising the steam temperature to metallurgical unsafe levels.

The second one is Expand the steam in the turbine in two stages, and reheat it in between. In other words, modify the simple ideal Rankine cycle with a reheat process. Reheating is a practical solution to the excessive moisture problem in turbines, and it is commonly used in modern steam power plants.

### The ideal regenerative cycle

A practical regeneration process in in steam power plants is accomplished by extracting or bleeding steam from turbine at various points. The device where feed water is heated by regeneration is called regenerator or feed water heater.

Some practical advantages of regeneration are:

- Condenser receive less mass flow rate of steam, less heat rejection. (Area of heat rejection under the curve of T-S diagram reduced).
- Mean temperature at which heat is added in boiler increases, this increase efficiency.
- Overall temperature difference in boiler is reduced, this causes less thermal stress.
- As mass flow rate of steam decreases at low pressure turbine, low pressure turbine blade length are smaller (less vibration results longer blade life).
- Reduces condenser size as it receives smaller quantity of steam.
- Boiler heat transfer is more efficient because smaller size.
- Provide convenient means of deaerating the feed water heater to prevent corrosion by removing air leaks in condenser.
- Optimum number of feed water heater is determined from economic consideration. (Advantage of increase in efficiency shall be greater than cost of feed water heater itself).

Some practical demerits of regeneration are:

- Complex plant structure.
- Increased initial and maintenance cost.
- Greater pressure losses in feed water and hence higher pumping cost.
- The reduced output due to regeneration is more than compensated by reduced heat rejection in the condenser.

**Combined gas vapor power cycles**

A more popular modification involves a gas power cycle topping a vapor power cycle, which is called the combined gas vapor cycle, or just the combined cycle. The combined cycle of greatest interest is the gas-turbine (Brayton) cycle topping a steam turbine (Rankine) cycle which has a higher thermal efficiency than either of the cycles executed individually.

This satisfy the highest possible temperature at which heat is added and the lowest possible temperature at which heat is rejected [19]. But the main anomalies of this power plant is limitation of type of fuel which is only liquid fossil fuel.

## 2.4) Geothermal power plants

Geothermal power is power generated by geothermal energy. Technologies in use include dry steam power stations, flash steam power stations and binary cycle power stations. Geothermal electricity generation is currently used in 24 countries. As of 2015, worldwide geothermal power capacity amounts to 12.8 GW, of which 28 percent or 3,548 MW are installed in the United States. International markets grew at an average annual rate of 5 percent over the last three years and global geothermal power capacity is expected to reach 14.5–17.6 GW by 2020 [13].

Based on current geologic knowledge and technology, the Geothermal Energy Association (GEA) estimates that only 6.5 percent of total global potential has been tapped so far, while the IPCC reported geothermal power potential to be in the range of 35 GW to 2 TW [12]. Countries generating more than 15 percent of their electricity from geothermal sources include El Salvador, Kenya, the Philippines, Iceland and Costa Rica. Geothermal power is considered to be a sustainable, renewable source of energy because the heat extraction is small compared with the Earth's heat content [14].

A flow sheet for the dry steam station cycle is shown in Figure 2.2. The geothermal fluid enters the well at the source inlet temperature, station 1. Due to the well pressure loss, the fluid has started to boil at station 2, when it enters the separator. The brine from the separator is at station 3, and is re-injected at station 4, the geothermal fluid return condition.

The steam from the separator is at station 5, where the steam enters the turbine. The steam is then expanded through the turbine down to station 6, where the condenser pressure prevails. The condenser shown here is air cooled, with the cooling air entering the condenser at station $C_1$ and leaving at station $C_2$. The condenser could be wet cooling tower or natural draft cooling, due to scarcity of water in most of geothermal power plants. The condenser hot well is at station 7. The fluid is re-injected at station 4 [13].

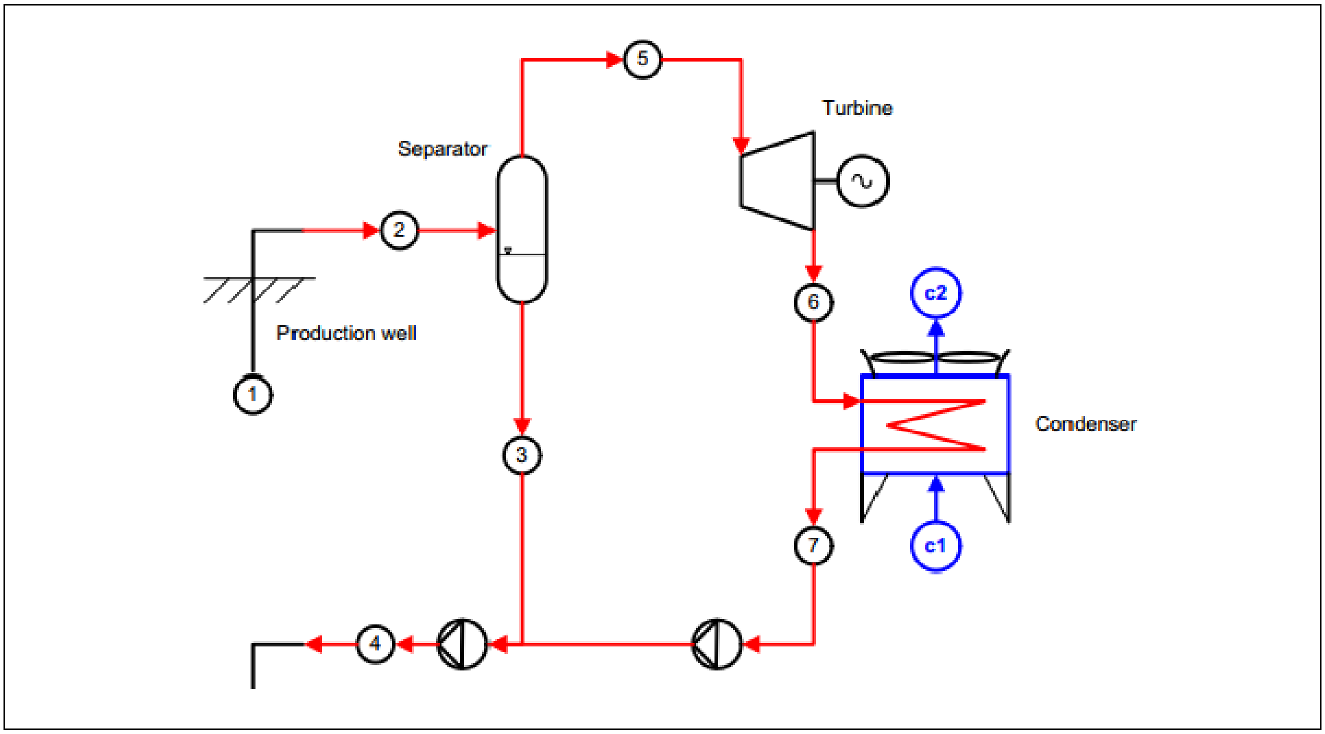


**Figure 2.2 Block diagram of dry steam station** [14]

A flow sheet for the flash steam station cycle is shown in Figure 2.3. The geothermal fluid enters the well at the source inlet temperature, station 1. Due to the well pressure loss the fluid has started to boil at station 2, when it enters the separator. The brine from the separator is at station 3, and is throttled down to a lower pressure level at station 8. The partly boiled brine is then led to a low pressure separator, where the steam is led to the turbine at station 9.

The turbine is designed in such a way, that the pressure difference over the first stages is the same as the pressure difference between the high and low pressure separators. The mass flow in the lower pressure stages of the turbine is then higher than in the high pressure stages, just the opposite of what happens in a traditional fuel fired power plant with a bleed for the feed water heaters from the turbine. The brine from the low pressure separator is at station 10, and is then re-injected at station 4, the geothermal fluid return condition. The steam from the high pressure separator is at station 5, where the steam enters the turbine. The low pressure steam enters the turbine a few stages later, at station 9. The steam is then expanded through the turbine down to station 6, where the condenser pressure prevails. The condenser shown here is air cooled, with the cooling air entering the condenser at station $C_1$and leaving at station $C_2$. The condenser hot well is at station 7. The fluid is re-injected at station 4 [13].

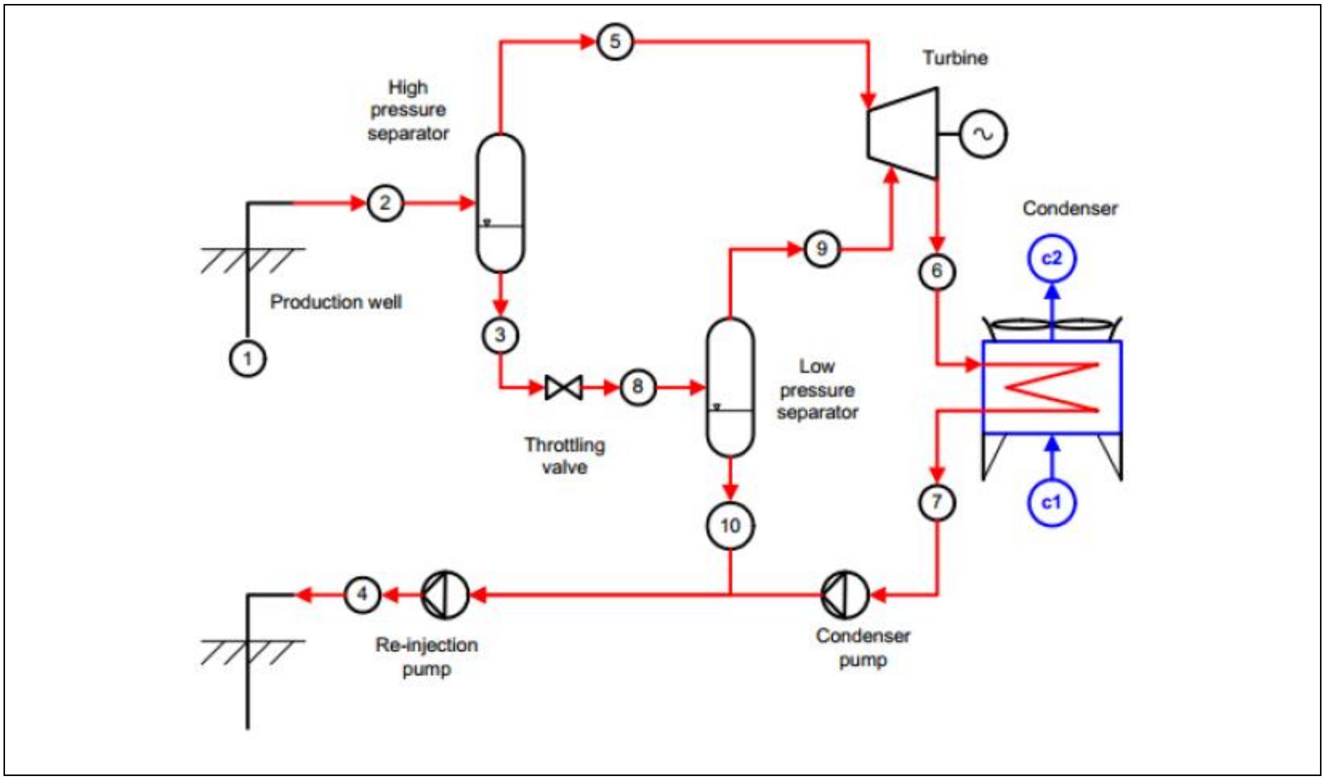


Figure 2.3 Block diagram of flash steam station [14]

### 2.4.1) Aluto Langano Geothermal Plant

Continuous operation of a geothermal power plant basically relies on the sustainable geothermal source and skill led operation of the resource and power plant. Major problems encountered are mostly related to the chemistry of geothermal water. Aluto Langano pilot plant has encountered many problems over the years of service.

The power plant is designed to generate a net output power of 7.28 MWe (8.52 MWe gross) with two units. These are:

- A geothermal combined cycle unit (GCCU), a steam turbine integrated with binary turbine that generates 3.9 MWe.
- An Ormat energy converter (OEC) with an output of 4.6 MWe (Ormat, 2001).

There are four production wells from which steam and brine are supplied to the power plant. The production wells are LA-3, LA-4, LA-6 and LA-8 and there is one reinjection well, LA-7. Well LA-3 and LA-6 are high enthalpy wells supplying steam to the GCCU and brine to a flash tank, used as a heat source for heating the isopentane in the OEC un it. Wells LA-4 and LA-8 are low-pressure wells supplying steam to the vaporizer of the OEC unit and brine to the flash tank. Each well has its own steam separator near the wellhead.

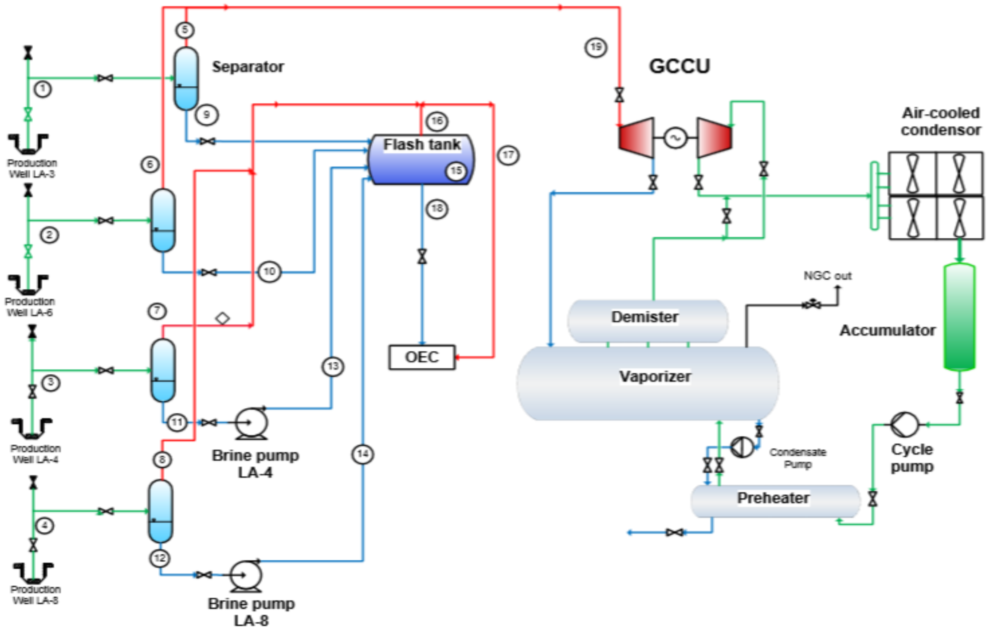


Figure 2.3 Aluto Langano Geothermal Combined Cycle Unit GCCU [14]

## 2.5) Heat exchanger and steam boiler

Heat exchanger is a device that exchanges heat energy from one medium to another. Those mediums could be a gas, liquid or solids. Boilers and condensers are the main examples of heat exchangers. The design of those components play a significant role on overall performance and efficiency of power plant. Some heat exchangers are direct type in which fluids are physically mixed. The others are indirect type in which the fluids are separated by a wall. Some examples of indirect type are parallel flow, counter flow and cross flow.

Steam generator or boiler is a common device which generates steam at a desired rate, temperature and pressure by burning fossil fuels and transferring the heat from heat combustion gases to water or steam. In nuclear power plants also transfer heat from nuclear reactor to steam at the safe operation temperature. In the case of electricity generation from Lava Lake, the source of the heat is transferred at an optimal desired rate for actual generation of electricity.

The two types of steam boiler are fire tube boiler and water tube boiler. In fire tube boiler, the tubes are filled with flue gases where as in water tube boiler the tubes are filled with water as its names implies. Both water tube and fire tube boilers have their own advantages and dis advantages. Both fire tube and water tube boilers have their own riser and down comer.

Boilers also have heat recovery equipment such as 1) Economizer, 2) Super heater, 3) Boiler (evaporator), 4) Reheater and 5) Air preheater.

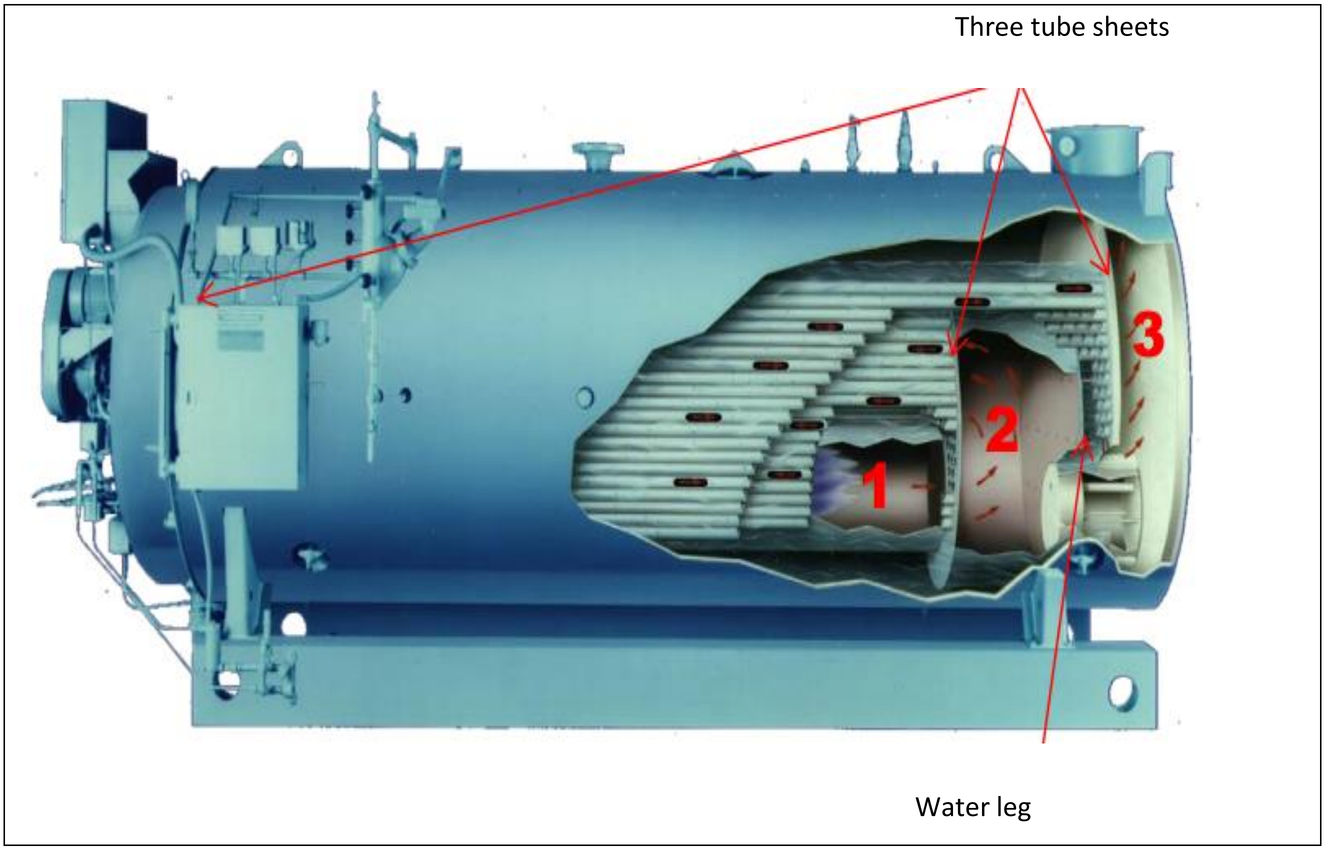


**Figure 2.4 Horizontal fire tube boiler [20]**

## 2.6) Previous Related works

### 2.6.1) Iceland Deep Drilling Project

The Iceland Deep Drilling Project (IDDP), in 2009, accidentally drilled into a magma reservoir about 2 kilometers below the surface, when it was planned to construct a conventional geothermal well. As an experiment on the IDDP, water poured down to the magma well to see how much energy it could generate, and they ended up creating the most powerful geothermal well ever drilled, generating some 30 megawatts of power [15].

The first phase of the IDDP was planned for drilling a depth of 4.5 km, with the aim of exploring for supercritical geothermal fluids, had to be completed at only 2104 m depth when >900 $^{o}$C magma flowed into it. After pulling up the drill string a few meters and maintaining circulation, colorless rhyolitic glass cuttings were returned, followed by abundant, darker, obsidian-like drill cuttings. It became clear magma had flowed into the drill hole [17]. However this unexpected result proved to be a case of serendipity.

Subsequently during a two year-long flow test it became the world’s hottest producing geothermal well, with a well head temperature of more than 450 $^{o}$C, flowing dry superheated steam at high pressures (40–140 bar) [16].

A large magma chamber, located at 3-7 km depth at the center of the caldera, is believed to be the heat source for a geothermal system currently supplying steam to the 60 MWe Krafla power plant. It was deemed not feasible to continue drilling deeper than 2104 m in well, given the equipment available. Therefore the well was completed with a cemented casing and a hanging slotted liner was set a few meters above the quenched magma [17].

Material tests and scrubbing experiments were carried out at the IDDP-1 well in the Krafla geothermal field in Iceland. The 450 $^{o}$C superheated steam contained acid gas (approx. 90 mg/kg HCl and 7 mg/kg HF) and was highly corrosive when it condensed making it unsuitable for utilization without scrubbing. The steam contained gaseous sulfur compound (80–100 mg/kg S), which could only be scrubbed from the steam with alkaline water. Experiments on corrosion and erosion resistance of metals and alloys were problematic to run because of equipment clogging by silica dust [18].

Although it was the most powerful geothermal well ever drilled, IDDP was different from conventional geothermal power plants. Unlike the case of conventional geothermal plant, working fluid or water was poured in to U shaped cemented casing, in which the source of water is the ocean that was no run out of in the case of IDDP. The main challenge related to this project is, extraction of power through around 4.5 km is economical.

The main difference between power generation from Iceland deep drilling project and Erta Ale Lava Lake is their thermo dynamic system. In Iceland water is supplied from the sea and its thermodynamic system is open system. But Erta Ale Lava Lake is located in Afar desert where there is no availability of water which is enough to operate by open system. Due to this reason brick coated steam boiler was designed to operate on closed thermodynamic system.

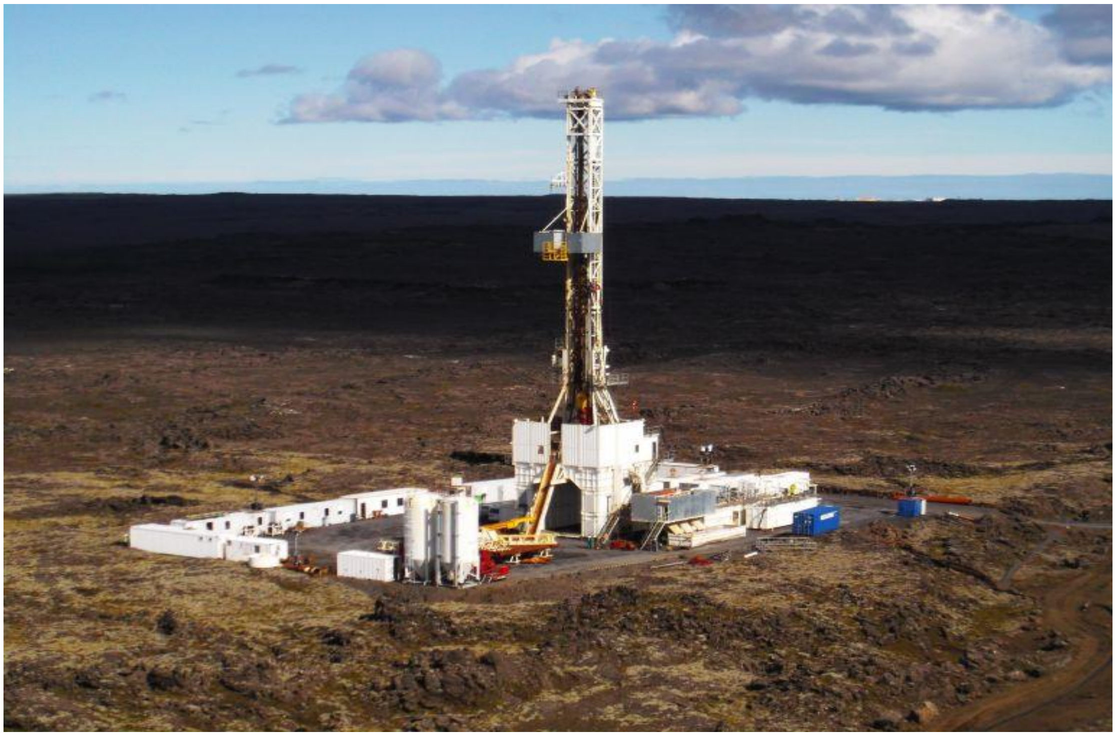


**Figure 2.5. Iceland Deep Drilling Project (IDDP) [15]**

### 2.6.2) Comparison of common power generation systems

Most of source of electric power in the world generated using conventional vapor power plants and nuclear power plants which mainly converts heat energy in to electrical energy through several processes. The following table shows the basic gap between common power plants and Erta Ale Lava Lake Power plant.

**Table 2.1 Comparison of some common ways of generation of electricity**

| No. | Type of power plant | Source of energy | Thermodynamic system | Thermodynamic cycle | Working fluid | Energy type | Environmental effect |
|---|---|---|---|---|---|---|---|
| 1 | Conventional Rankine cycle power plant | Coal | Closed | Rankine | Water | Non renewable | Polluter |
| 2 | Geothermal power plant | Underground steam | Open | Rankine | Water | Renewable | Non Polluter |
| 3 | Nuclear power plant | Uranium | Closed | Rankine | Water | Non renewable | Dangerous |
| 4 | Combined cycle power plant | Natural gas | Combined | Bryton & Rankine | Water & Air | Non renewable | Polluter |
| 5 | Gas power cycle power plant | Natural gas | Open | Bryton | Air | Non renewable | Polluter |
| 6 | Solar thermal power plant | Solar radiation | Closed | Rankine | Water | Renewable | Non Polluter |
| 7 | Magneto hydro dynamic power plant | Natural gas | Closed | Rankine | Water | Non renewable | Polluter |
| 8 | Iceland Magma power plant | Magma | Open | Rankine | Water | Renewable | Non Polluter |
| 9 | Erta Ale Lava Lake power plant | Magma | Closed | Rankine | Water | Renewable | Non Polluter |

# Chapter Three

## 3) General characteristics and energy of Erta Ale Lava Lake

### 3.1) Introduction

Thermo dynamics governs how the entire universe operates and governs how the entire universe will end. The two laws of thermodynamics are fundamental laws of nature or physics. Those laws are the first law of thermodynamics and the second law of thermodynamics which are always true until the end of time. The first law of thermodynamics states that the amount of energy in a universe remains constant. All suns and stars in a universe have a limited amount of energy.

Energy can transferred from one object to another, but neither created nor destroyed. Energy per particle inside object is temperature. Energy is not destroyed when friction slows down the object because friction speeds up the molecule, increase temperature. Energy is also not destroyed when temperature goes back down, because the motion is dispersed or detached to the surrounding. There is also a hidden form of energy that all life's and technology depends on, Chemical energy in the food we eat and fuel we burn. So, human being and all other living things are a device which transform chemical energy in a food to other useful energy commonly called mechanical energy and release heat during the process.

Mass is also a form of Nuclear energy. Mass is neither created nor destroyed in any of the reaction. When certain atomic nucleus combine or separate, some masses completely disappear from the universe. The energy of this missing mass is then released. Nucleus splitting apart or fission reaction power nuclear reactor, whereas nucleus combining or fusion reaction powers sun and stars. Energy is responsible for everything and its activities that happens in a universe.

Second law of thermodynamics states that entropy of the universe can only go up and never go back down. Entropy also applies to energy. This is the reason why life in a universe is possible and will end. The dispersion of energy as heat increases entropy. All engines and life forms need to dissipate heat to colder object to keep operating. However all objects eventually reaches the same temperature which commonly called thermal equilibrium if we will wait long enough, and then all engines and life stop operating once for end.

## 3.2) Overview of internal structure of the Earth and Lava tube

The internal structure of the Earth is layered in spherical shells: an outer silicate solid crust, a highly viscous asthenosphere and mantle, a liquid outer core that is much less viscous than the mantle, and a solid inner core. Scientific understanding of the internal structure of the Earth is based on observations of topography and bathymetry, observations of rock in outlier, samples brought to the surface from greater depths by volcanoes or activity. Analysis of the seismic waves that pass through the Earth, measurements of the gravitational and magnetic fields of the Earth, and experiments with crystalline solids at pressures and temperatures characteristic of the Earth's deep interior.

The force exerted by Earth's gravity can be used to calculate its mass. Astronomers can also calculate Earth's mass by observing the motion of orbiting satellites. Earth's average density can be determined through gravimetric experiments, which have historically involved pendulums. And the mass of Earth is about $6\times10^{24}$ kg [30].

The Earth's crust ranges from 5–70 kilometers in depth and is the outermost layer. The thin parts are the oceanic crust, which underlie the ocean basins 5–10 km and are composed of dense (mafic) iron magnesium silicate igneous rocks, like basalt. The thicker crust is continental crust, which is less dense and composed of (felsic) sodium, potassium, Aluminum, silicate rocks, like granite. Many rocks now making up Earth's crust formed less than 100 million years ago, however, the oldest known mineral grains are about 4.4 billion ($4.4\times10^{9}$) years old, indicating that Earth has had a solid crust for at least 4.4 billion years [31].

Earth's mantle extends to a depth of 2,890 km, making it the thickest layer of Earth. It is separated from crust by structure called Moho, which its surface temperature reaches 1900 $^{o}$C. The mantle is divided into upper and lower mantle. The upper and lower mantle are separated by the transition zone. The pressure at the bottom of the mantle is ≈140 GPa (1.4 Million atm). The mantle is composed of silicate rocks that are rich in iron and magnesium relative to the superimposing crust. The average density of Earth is 5.515 g/cm$^{3}$. Because the average density of surface material is only around 3.0 g/cm$^{3}$, we must conclude that denser materials exist within Earth's core. The liquid outer core surrounds the inner core and is believed to be composed of iron mixed with nickel and trace amounts of lighter elements [31].

A lava tube is a natural conduit formed by flowing lava which moves beneath the hardened surface of a lava flow. Tubes can drain lava from a volcano during an eruption, or can be extinct, meaning the lava flow has terminated, and the rock has cooled and left a long cave. A lava tube is formed when a low-viscosity lava flow develops a continuous and hard crust, which thickens and forms a roof above the still-flowing lava stream. Tubes form in one of two ways: either by the crusting over of lava channels, or where the lava is moving under the surface [30].

Earth's internal engine is running about 1,000 degrees Celsius (about 1,800 degrees Fahrenheit) hotter than that of previously measured, providing a better explanation for how the planet generates a magnetic field, a new study has found [25].

The melting point of iron at high precision has measured in a laboratory, by the team of scientists and then drew from that result to calculate the temperature at the boundary of Earth's inner and outer core now estimated at 6,000 C (about 10,800 F). That's as hot as the surface of the sun.

The difference in temperature matters, because this explains how the Earth generates its magnetic field. The Earth has a solid inner core surrounded by a liquid outer core, which in turn, has the solid, but flowing, mantle above it. There needs to be a 2,700-degree F (1,500 $^0$C) difference between the inner core and the mantle to spur "thermal movements" that along with Earth's spin create the magnetic field [26].

Extrapolating from the measurement, scientists estimated the boundary between Earth's inner and outer core is a searing 10,832 F, give or take about 930 degrees, at a pressure of 3.3 million atmospheres (or 3.3 million times the atmospheric pressure at sea level).

But Afar triangle, which is so called Triple Junction was a result of pulling apart of three tectonic plates, i.e Nubian, Somalian and Arabian plates. The plates are developing divergent tectonic plate boundary, where two African plates is in a process of splitting in to two tectonic plates, called Somali and Nubian plate, at a rate of 6-7 mm annually. Within 10 million years, Somali plate will break off and a new ocean basic will form [21].

On the other hand, the level of the lake fluctuates between 80 m below crater rim and sometimes the lava over flows. In addition to this, the lake is continuously active and there is continuous eruption within a few decades. For instance, in 2010, the estimated total volume of lave erupted is approximately 0.006 $km^3$ 0r 6 million $m^3$.

Hypothesis on the recorded data's and the above observed characters of the lake shows that, the lake is continuously active and directly related to the inner part of the earth through magma tube and magma reservoir. Geothermal gradient is the rate of increasing temperature with respect to increasing depth in the Earth's interior. Away from tectonic plate boundaries, it is about 25–30 °C/km of depth near the surface in most of the world. Strictly speaking, geo-thermal necessarily refers to the Earth but the concept may be applied to other planets [25].

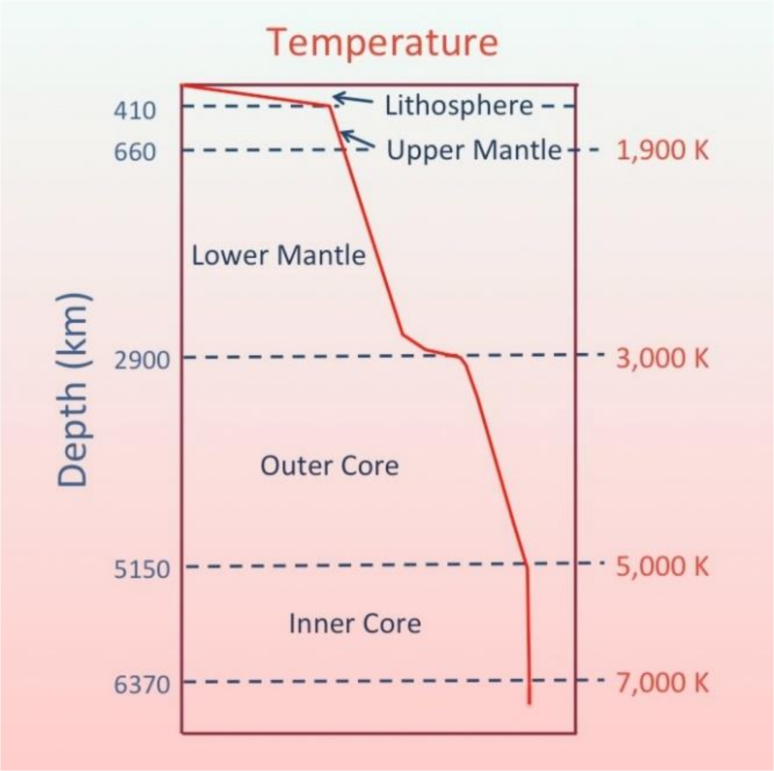


**Figure 3.1 Schematic view of estimated Temperature profile of the inner Earth [26]**

## 3.3) Ethiopian rift valley and power capacity

The Great East African Rift system divided Ethiopia in to two from northeast to southwest. This allow regional high heat flow due to thin crust. For the presence of geothermal that Ethiopia is involving significantly along with some of the East African countries (Eritrea, Djibouti, Kenya, Uganda and Tanzania), the Rift has created a conducive environment. The area of about 150,000 km$^2$ that is close to 12% of the total land area was covered by the rift [24].

Both in Kenya and Ethiopia, a single field could support over 100 MW based on available scientific information and practices on the rift geothermal systems. Taking this; the power density for most geothermal fields worldwide, i.e. 8 MW/km$^2$ at 230°C and up to 30 MW/km$^2$ at 300°C (Grant, 2000); and the size, frequency and extent of volcanic and hydrothermal activities all along the 1,500 km length of the Ethiopian Rift, it is possible to assume the presence of a huge geothermal energy base in Ethiopia.

From south to north, the priority areas for geothermal electric power development in the main Ethiopian rifts are Abaya, Corbetti, Aluto-Lanagnao, Tulu Moye, Gedemsa, Boseti Guda, Boseti Bericha, Kone, Fentale and Dofan. Deep exploration drilling, which was the first experience in Ethiopia had carried out in the Alutu Langano geothermal field in the early to mid-1980s [24].

In 2016, Ethiopian total electrical generation capacity is 3,810 MW from hydro plant, 324 MW from wind, 7 MW from solar, 7 MW from geothermal, and 112 MW from Diesel plant and total 4,260 MW. At growth and transformation plan GTP II, the country planned to generate 11,015 MW from hydro plant, 1,520 MW from wind, 300 MW from solar, 1,270 MW from geothermal, and 112 MW from Diesel plant and total 14,217 MW [26]. But Ethiopia has energy potential of 45,000 MW from hydro plant, 1,350,000 MW from wind, 10,000 MW from geothermal, and total 1,405,000 MW.

The country has also 1120 million tons of wood, 20 million tons of agricultural waste, 113 billion cubic meter natural gas, 300 million tons coal and 253 million tones oil shale [26]. This is the only explored potential up to now and the new exploration would significantly altered the figure.

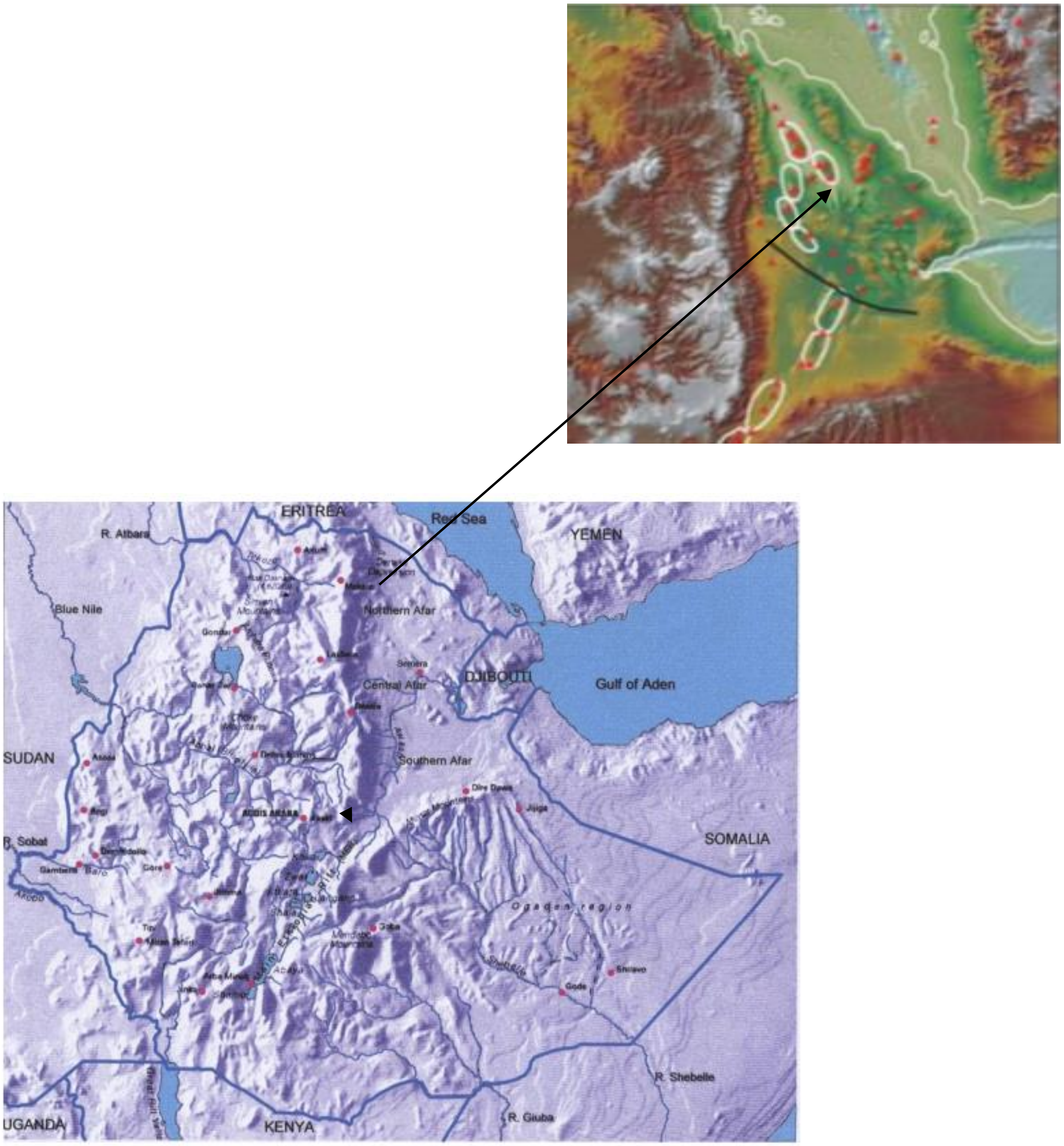


Figure 3.2 Physiographic map of Ethiopia and Erta Ale Lava Lake [24]

## 3.4) Thermal Imaging of Ethiopian Erta Ale active Lava lake

According to Oppenheimer and Francis 1998, Erta Ale Lava Lake is perhaps active for at least 100 years up to the current. Landsat Thematic Mapper (TM) infrared measurements have been used to remote sensing investigation of erta ales thermal regime by oppenheimer and Francis 1997 and Harris et al 1999 for Remote sensing investigations of Erta 'Ale's thermal regime. But, the surface losses of heat from this lava lake estimated in each lake differ by an order of magnitude (100-400) and 14-27 MW, respectively.

In 2001 Oppenheimer and Gezehagn Yirgu were made an observation from the crater rim, a vertical distance of around 70 m above the surface of the lake, using an Agema Thermovision, 550 infrared camera equipped with a stirling-cooled, focal plane array of PtSi detectors (3.6 to 5.0 micrometer response) [14].

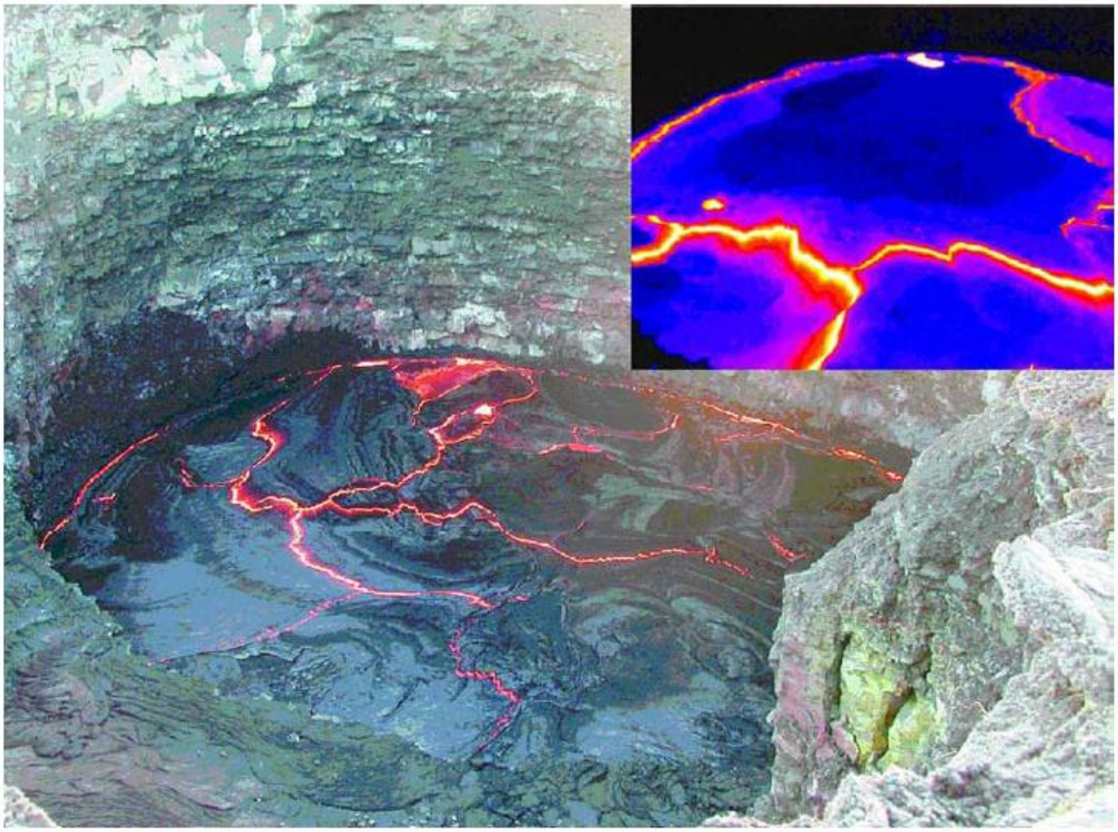


**Figure 3.3 Digital photograph of Erta Ale Lava Lake [14]**

More than 300 images were collected in total, covering a range of surface behavior from almost complete crusting over of the lake, to energetic upwelling of molten lava at the surface. The images reveal extraordinary detail in the thermal structure of the lake surface. Away from incandescent cracks, the crust temperature does not fall below ≈ 300 $^{o}$C. The maximum observed temperature of 1174$^{o}$C is consistent with direct measurements of ≈ 1100 to 1200$^{o}$C for lava and gas emitted by Erta Ale in early 1970s [14].

Total estimated area of the lake is $A = 6200\ m^2$, which is obtained by surveying the lake perimeter with laser-ranging binoculars. The three cases yield radiative heat fluxes of ≈ 70, 100, and 150 MW. Sensible heat losses can be estimated to be 50 % of radiative heat loss. Indicating combined radiative and sensible heat loss of ≈ 100-200 MW [14].

The thickness of the skin, *h*, on the lake (comprising a solid carapace and an underlying mushy layer of crystals and melt) scales with time *t* as follows.

$$h \approx \{(T_l - T_s)\, C_p \mathrm{k}^{t/L}\}^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

Where $T_l$ is the equilibrium freezing temperature (≈1170 °C), $Ts$ is the skin surface temperature (≈400 °C), and $Cp$ the specific heat (≈$10^3$ J $kg^{-1}C^{-1}$), $L$ the latent heat (≈$4 \times 10^{5}$ $Jkg^{-1}$) and k the thermal diffusivity (≈$5 \times 10^{-7}$ $m^2s^{-1}$) of the lava (values from Hardee 1980). This suggests *h* reaches ≈ 10 mm within 2 min of magma upwelling at a ‘rift’ [14].

A heat loss of 200 MW is equivalent to about 500 kg $s^{-1}$ of crystallization (for a latent heat for basalt of $4 \times 10^5$ J $kg^{-1}s^{-1}$). For a 5% difference in crystallinity of magma entering and leaving the lake, this would imply a mass flux into (and out of) the lake of ≈ $10^4$ kg $s^{-1}$ (≈4 $m^3$ $s^{-1}$ for a typical basalt density) and a significant density contrast of ≈25-45 kg/$m^3$ (for assumed density of basalt of 2600–2700 kg/$m^3$ and mafic mineral density of 3200 to 3500 kg /$m^3$). Larger pulses of magma influx into the lake can be accommodated by faster resurfacing rates (i.e. greater ‘rift’ length or spreading rate).

Oppenheimer and Gezehagn Y. concluded that, estimated radiative and sensible heat flux of 100-200 MW for the ertale lava lake is the most reliable to date. They propose that crystallization could support sustained heat loss from Lake Surface and drive convection between the lake and the deeper and larger magma reservoir. It is obvious that the sustained replenishment of heat prevents the lake from solidification.

## 3.6) Concept of electricity generation from Erta Ale Lava Lake

Erta Ale is a continuously active basaltic shield which is found in the Afar Region of northeastern Ethiopia. It is situated in the particular place Afar Depression, 13°36′N 40°40′E. Crossing the border with Eritrea, this is a badland desert. Having the height of 613 above the sea level, this lava lake is the most active volcano in Ethiopia. One or two active lava lakes at the peak, intermittently overflow on the south side of the volcano. Its temperature reaches up to 1200 $^{o}$C. Volcanoes with lava lakes are very rare in our world: there are only six in number includes Kilauea (Hawaii), Nyiragongo (Democratic Republic of Congo, formerly Zaire), Erebus (Antarctica) and Erta 'Ale (Ethiopia) [11].

**Figure 3.4 Erta Ale Lava Lake [12]**

The first task to capture this potential is proper estimation of three dimensional temperature distribution with the lowest possible error. Temperature at cross section of the lake along horizontal direction is assumed to be uniform. Linear interpolation is used to calculate the temperature distribution along vertical axis. Once temperature distribution is known, then potential of this continuously flowing lava lake is estimated by optimization.

Once the potential is estimated, the main problem of converting this potential using ordinary boiler material which safely operate at this temperature. It is also difficult to install boiler in such uncomfortable volcanic caldera. But the main objective is to generate electricity by eliminating all the problems. To avoid the problem of boiler materials, steel boiler is coated with selected brick which has the highest possible overall heat transfer coefficient U.

## Chapter Four

# 4) Mathematical modeling of temperature distribution and energy potential of Erta Ale Lava Lake

## 4.1) Introduction

Calculation or estimation of temperature distribution and energy potential of any power plant are easy within specified independent variables. The three most important independent variable which determine the potential of the lake is:

1. Temperature measured at least, at two points, along vertical direction.
2. The exact geological information of the lake weather its volume is limited or directly joined with the core of the earth.
3. Tangible evidence weather the lake is characterized by divergent force or convergent force of the three tectonic plates.

It is very crucial to consider the above three cases to fully design the plant. The third case or idea, is the most important hypothesis, which totally reduces the problems related to the first two cases and make this project possible by total elimination of tension about limitation of the potential through a time.

In first case, even though maximum recorded temperature 1200 $^{o}$C on the surface of the lake represent temperature at upper layer of the lake, which is assumed to be uniform along horizontal direction, there is no sufficient information about the rate of increment of temperature per unit depth.

Hypothesis on the recorded data’s and the above observed characters of the lake shows that, the lake is continuously active and directly related to the inner part of the earth through magma tube and magma reservoir.

## 4.2) Mathematical modeling of temperature distribution of the lake within the depth of 1500 m

Temperature distribution of the lake can be calculated by finite difference method or by interpolation using 1200 $^{o}$C as a reference at upper point and 6727 $^{o}$C as a reference at depth of 6371 km (the center of the earth). At this point pressure is 3.6 million atmosphere or 360 GPa.

In our case, the pressure gradient is relatively very low and temperature within 1500m is almost the same as that of the surface before exposing to atmospheric air and temperature gradient due to pressure variation is almost negligible.

To simplify estimation of temperature distribution within small interval for heat transfer analysis, depth of 1500m, in which it is very difficult to install the boiler if depth is greater than this depth was chosen. But, the main constraint that limit the length of the pipe is high density of magma at the depth greater than 1.5 km. The main reason of limitation of the depth and ways of optimization of this depth will be discussed in detail in chapter 5.4 of this work.

Assuming the rate at which temperature increases towards the center of the earth linear, linear interpolation method is used to estimate temperature variation through depth of the earth.

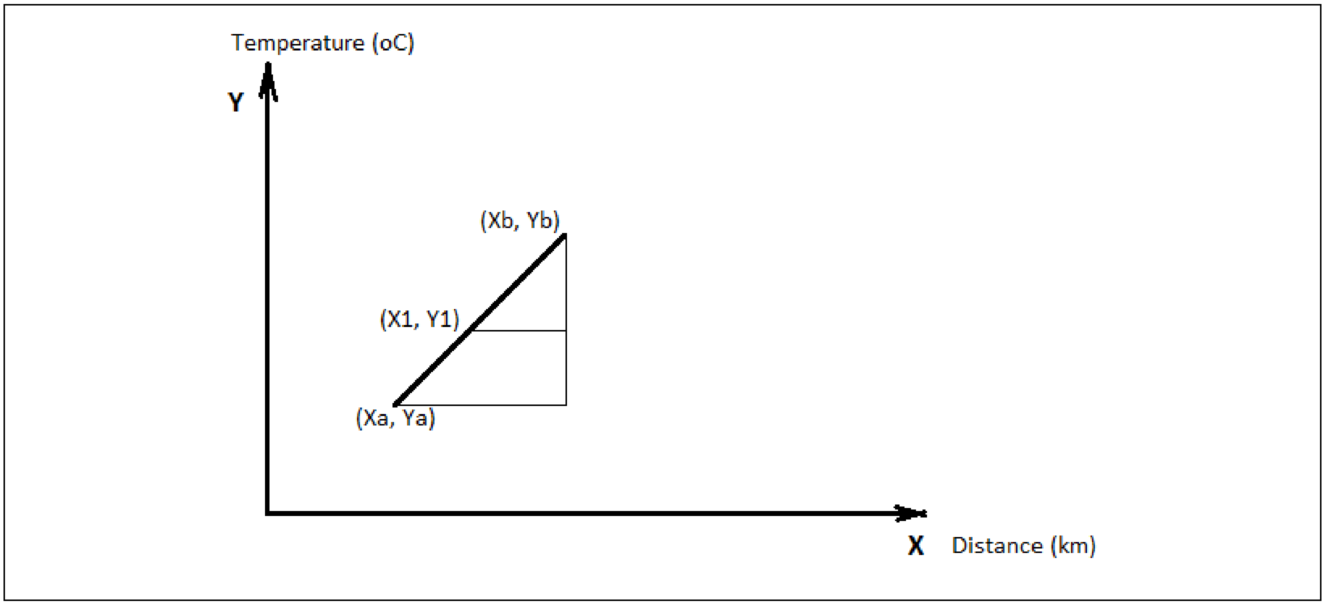


**Figure 4.1 Linear interpolation**

$$Y_n = Y_b - ((Y_b - Y_a) / (X_b - X_a)) (X_b - X_a) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

Where $Y_n$ is value of temperature which is calculated at different distance through the diameter of the earth.

**Table 4.1 Temperature distributions towards the core of the Earth**

| X = Distance | Value (m) | Y = temperature | (Yb - Ya)/(Xb - Xa) | Value ($^0$C) |
|---|---|---|---|---|
| Xa | 0 | Ya | 0.000867525 | 1200.000 |
| X1 | 200 | Y1 | 0.000867525 | 1200.174 |
| X2 | 400 | Y2 | 0.000867525 | 1200.347 |
| X3 | 600 | Y3 | 0.000867525 | 1200.521 |
| X4 | 800 | Y4 | 0.000867525 | 1200.694 |
| X5 | 1000 | Y5 | 0.000867525 | 1200.868 |
| X6 | 500000 | Y1 | 0.000867525 | 1633.762 |
| X7 | 1000000 | Y2 | 0.000867525 | 2067.525 |
| X8 | 1500000 | Y3 | 0.000867525 | 2501.287 |
| X9 | 2000000 | Y4 | 0.000867525 | 2935.049 |
| X10 | 2500000 | Y5 | 0.000867525 | 3368.812 |
| X11 | 3000000 | Y6 | 0.000867525 | 3802.574 |
| X12 | 3500000 | Y7 | 0.000867525 | 4236.337 |
| X13 | 4000000 | Y8 | 0.000867525 | 4670.099 |
| X14 | 4500000 | Y9 | 0.000867525 | 5103.861 |
| X15 | 5000000 | Y10 | 0.000867525 | 5537.624 |
| X16 | 5500000 | Y11 | 0.000867525 | 5971.386 |
| X17 | 6000000 | Y12 | 0.000867525 | 6405.148 |
| Xb | 6371000 | Y13 | 0.000867525 | 6727.000 |

The temperature value in a table shows that, through the depth of study or 1500m, temperature gradient is less than 1 $^o$C which is almost negligible. This generally shows that the temperature at the core of the earth around 7000 k decreases at the rate around 1 $^o$C per kilo meter and it approaches to 1200 at the surface of the lake. Our depth of study is relatively very small which compared to radius of the earth which is 6371 km.

In general, three dimensional temperature distribution of the lake is assumed to be uniform 1200 $^o$C within the depth of 1500 m.

## 4.3) Estimation of total energy content of the Earth and energy potential per unit depth of Erta Ale Lava Lake

The total energy potential of the earth depend on average temperature of internal structure of the earth, average specific heat capacity of magma inside the earth, volume of the earth and density of the earth. Even though the pressure of magma is very high which reaches 3.6 million atmosphere or 360 million kPa at the interior of the earth, assuming average density magma 3000 kg/m$^3$, specific heat capacity of magma 10$^3$ J/kg$^o$C. But, the shape of the earth is sphere. Due to temperature difference towards the center of the earth, it is not easy to calculate this total energy content. To simplify this difficulty, assuming density of magma constant, it is required to discretize the earth in to shells to estimate total energy content of the earth. The following table shows average temperatures at an interval of 5000 km. Volume of the Earth is calculated by:

$$Q_{total} = \sum_{i=1}^{n13} Qi \qquad \text{and} \qquad Qi = \sum_{i=1}^{n13} \rho ViCp\Delta Ti$$

**Figure 4.2 3D discretization of the earth in to shells**

### Table 4.2 Estimation of total energy content of the Earth

| Value (0C) | Vi = pi*D3/6 | value in m3 | Vi = Vi-V(i-1) | Qi = p*V*Cp*T | X = Distance | Diameter (m) | Density (Kg/m3) |
|---|---|---|---|---|---|---|---|
| 1473.00 | Va | 0 | 0 | 0 | Xa | 0 | 3000 |
| 1473.17 | Vb | 0 | 0 | 0 | X1 | 0 | 3000 |
| 1473.34 | Va | 0 | 0 | 0 | X2 | 0 | 3000 |
| 1473.52 | Vb | 0 | 0 | 0 | X3 | 0 | 3000 |
| 1473.69 | Va | 0 | 0 | 0 | X4 | 0 | 3000 |
| 1473.86 | Vb | 0 | 0 | 0 | X5 | 0 | 3000 |
| 1906.76 | V1 | 1.08266E+21 | 1.78338E+20 | 1.02014E+30 | X1 | 12742000 | 3000 |
| 2340.52 | V2 | 9.0432E+20 | 2.07763E+20 | 1.45883E+30 | X2 | 12000000 | 3000 |
| 2774.28 | V3 | 6.96557E+20 | 1.73223E+20 | 1.44171E+30 | X3 | 11000000 | 3000 |
| 3208.04 | V4 | 5.23333E+20 | 1.41823E+20 | 1.36493E+30 | X4 | 10000000 | 3000 |
| 3641.81 | V5 | 3.8151E+20 | 1.13563E+20 | 1.24073E+30 | X5 | 9000000 | 3000 |
| 4075.57 | V6 | 2.67947E+20 | 8.84433E+19 | 1.08137E+30 | X6 | 8000000 | 3000 |
| 4509.33 | V7 | 1.79503E+20 | 6.64633E+19 | 8.99117E+29 | X7 | 7000000 | 3000 |
| 4943.09 | V8 | 1.1304E+20 | 4.76233E+19 | 7.06221E+29 | X8 | 6000000 | 3000 |
| 5376.86 | V9 | 6.54167E+19 | 3.19233E+19 | 5.14942E+29 | X9 | 5000000 | 3000 |
| 5810.62 | V10 | 3.34933E+19 | 1.93633E+19 | 3.37539E+29 | X10 | 4000000 | 3000 |
| 6244.38 | V11 | 1.413E+19 | 9.94333E+18 | 1.8627E+29 | X11 | 3000000 | 3000 |
| 6678.14 | V12 | 4.18667E+18 | 3.66333E+18 | 7.33929E+28 | X12 | 2000000 | 3000 |
| 7000.00 | V13 | 5.23333E+17 | 5.23333E+17 | 1.099E+28 | X13 | 1000000 | 3000 |
| | | | | 1.03362E+31 | | | |

From the above table, the total energy content is estimated to be approximately $10^{31}$ Joule which is approximately 100 billion times current worldwide energy consumption and 10 trillion times current Ethiopian energy consumption. This is also equal to that of the value estimated by scientists.

By similar fashion, after estimating average temperature, specific heat capacity, the volume and density, the energy potential per unit depth of the lake is calculated by:

$$Q_{p.u.d} = \rho \text{ x } V \text{ x } C_p \text{ x } \Delta T = 2600 \text{ kg/m}^3 \text{ x } 6200 \text{ m}^3 \text{ x } 1000 \text{ J/kg}^o\text{C x } 1200 \text{ }^o\text{C} = 19.3 \text{ x } 10^{12} \text{ J/m}$$

But the real or actual power potential of this lake is calculated depending on special type riser and down comer of the system in next chapter.

# Chapter Five

## 5) Design of special type steam boiler and estimation of power potential of Erta Ale Lava Lake

### 5.1) Introduction

In a design process of generation of electricity from erta ale Lava Lake, the first task is to make a possibility of generation using careful design of steam generator. Once possibility of generation is realized, optimization and proper utilization of the resource is very crucial. To realize the possibility of generation, it is very important to consider, the melting point of the lava, actual temperature of lava which is approximately 1200 $^{o}$C in comparison with melting point of steel which is approximately 1425 $^{o}$C. In the case of power potential, the lake is assumed to be continuous and directly joined with the mantle the earth. Total energy content of the earth is estimated to be $10^{31}$ Joule or $2.78x10^{18}$ GWH. This shows that power source of the plant is relatively assumed to be unlimited through the time.

### 5.2) Design of brick coated steam generator and Temperature Profile at different point through cross section of boiler pipe

The main challenges of this study is a very high temperature which reaches 1200 $^{o}$C which affect the performance of boiler but it is not strong enough to melt the steel. Even though melting point of steal which mentioned above is greater than that of minerals of rock, for proper performance operating temperature must be less than melting point of mineral rock. Melting point of steal and lava is shown in a below table.

**Table 5.1 Melting point of rock materials and carbon steel**

| Approximate Temperature (°C) | Minerals which are molten |
|---|---|
| 1200 | All molten |
| 1000 | Olivine, pyroxene, Ca-rich plagioclase |
| 800 | Amphibole, Ca/Na- plagioclase |
| 600 | Quartz, K-feldspar, Na-plagioclase, micas. |
| 1425 | Carbon steel |

Thickness of the steel pipe depends on maximum temperature and maximum pressure inside and outside the pipe. Maximum pressure inside a system is limited to 180 bar in modern power plants due to difficulty to design pipes. Maximum temperature of steam inside the pipe is also limited to 560 $^{o}$C due to metallurgical property. But turbine is far from power source and due to heat losses and friction losses in supply pipes the temperature increases to at least 600 $^{o}$C. This increase overall efficiency of plant. So the temperature inside pipe or operating temperature is limited to 600 $^{0}$C.

Assuming yield strength of steel pipe 1500 MP at an operating temperature thickness of steel is calculated by;

$$t = (p \times d) / (2 \times \sigma_H) \quad \ldots\ldots (5.1)$$

Where; t is thickness of steel, p is operating pressure, d is internal diameter of pipe and $\sigma_H$ yield strength of steel pipe. But, it is required to design the thickness in actual case in extreme detail.

$$t = (18 \text{ MPa} \times 0.58) / (2 \times 1500 \text{ MPa}) = 0.00348\text{m} = 3.48\text{mm}$$

In general, the melting point of steel 1425 $^{o}$C is greater than a maximum lava temperature 1200 $^{o}$C. But at this temperature the pipe may not overcome the operating pressure. Even though it is possible to reduce the temperature inside and outside the pipe, by adjusting the flow rate of steam in a pipe, there are three main cases that we shall be considered.

- The temperature inside the pipe (temperature of steam) is limited to 600 $^{o}$C due to metallurgical property of turbine.
- The maximum temperature outside the pipe must not exceed 1425 $^{o}$C. But maximum temperature of lava is 1200 $^{o}$C which is safe under given condition.
- The minimum temperature outside the pipe shall not fall below 900 $^{o}$C in order to avoid solidification of lava around boiler although maximum output power is attained at the highest possible temperature up to 1200 $^{o}$C. At 600 $^{o}$C all lava components are solidified. But at 900 $^{o}$C, almost all components of lava is liquid and this shows that if the temperature of lava fall below 900 $^{o}$C there is high probability of solidification of lava.

The above constraints limits our boiler design and can be used as independent variable to calculate the maximum possible heat transfer from lava to steam.

For one dimensional conduction in a plane wall, temperature is a function of the x coordinate only and heat is transferred exclusively in this direction. Heat transfer occurs by convection from the hot fluid at $T_{\infty,1}$ to one surface of the wall at $T_{s,1}$, by conduction through the wall, and by convection from the other surface of the wall at $T_{s,2}$ to the cold fluid at $T_{\infty,2}$. For steady state conditions with no distributed source or sink of energy within the wall, the appropriate form of the heat equation is;

$$d/dx\ (k \times dT/dX) = 0 \quad \text{(5.2)}$$

Equivalent thermal circuits used for more complex systems, such as composite walls. Such walls may involve any number of series and parallel thermal resistances due to layers of different materials. Consider the series composite wall, one dimensional heat transfer rate for this system can be expressed as:

$$q_x = (T_{\infty,1} - T_{\infty,4}) / \sum R_t = (T_{\infty,1} - T_{\infty,4}) / ((1/h_1A) + (L_A/K_AA) + (L_B/K_BA) + (L_C/K_CA) + (1/h_2A)) \quad \text{(5.3)}$$

With composite systems, it is often convenient to work with an overall heat transfer coefficient, U, which is defined by an expression analogous to Newton's law of cooling. Accordingly,

$$q_x = U \times A \times \Delta T \quad \text{(5.4)}$$

Assuming surface of the pipe as radial system, the rate of heat transfer in one dimension for the steel and the magma for unit area can be estimated by,

$$q_x = (T_{\infty,1} - T_{\infty,2}) / \sum R_t = (T_{\infty,1} - T_{\infty,2}) / ((1/h_1A_i) + ((1/2\pi KL) \ln (r_o/r_i)) + (1/h_2A_o)) \quad \text{(5.5)}$$

And the equation in a denominator, can be expressed analogously by electrical resistance, and thermal resistance is;

$$R_t = 1/h_1A_i + (1/2\pi KL) \ln (r_o/r_i) + 1/h_2A_o \quad \text{(5.6)}$$

Since these is analogs to connection in series;

$$q_x = (T_{\infty,1} - T_{s,1}) / (1/h_1A_i) = (T_{s,1} - T_{s,2}) / (1/2\pi KL) \ln (r_o/r_i) = (T_{s,2} - T_{\infty,2}) / (1/h_2A_o)) \quad \text{(5.7)}$$

To calculate temperature distribution at each point on steel pipe first we shall calculate heat transfer per unit area; ($q_x$'),

$$q_x' = (T_{\infty,1} - T_{\infty,2}) / (1/h_1) + (L/K) + (1/h_2)$$

$$= (1473\ K – 873\ K) / (1/300\ W/m^2K) + (0.00348m/30\ W / m.K) + (1/200\ W/m^2K)$$

$$= 71090\ W/m^2$$

Where,

- $T_{\infty,1}$ and $T_{\infty,2}$ are a limited fluid lava and steam temperature which are 1473 K and 873 K respectively.
- $h_1$ is estimated heat transfer coefficient of fluid lava which is around 140 $W/m^2K$
- $h_1$ is estimated heat transfer coefficient of steam which is around 200 $W/m^2K$
- K is thermo conductivity of steal at a given temperature which is 30 W/m.K.

Using calculated heat transfer rate per unit area, temperature profile of steal is calculated by;

$$q_x' = (T_{\infty,1} – T_{s,1}) / (1/h_1) \ldots\ldots (5.8)$$

And from this; $T_{s,1} = T_{\infty,1} – (q_x' / h_1) = 1473\ K – (71090\ W/m^2 / 140\ W/m^2K) = 1,236\ K$ or 963 $^oC$

$T_{s,2} = T_{\infty,2} + (q_x' / h_2) = 873\ K + (71090\ W/m^2 / 200\ W/m^2K) = 1,228\ K$ or 955 $^oC$

This shows that, $T_{s,1}$, which is 963 $^oC$ is a temperature little bit greater than the optimized allowable temperature 900 $^oC$, that has been already assumed in this study. To optimize this temperature brick is used to minimize outer temperature.

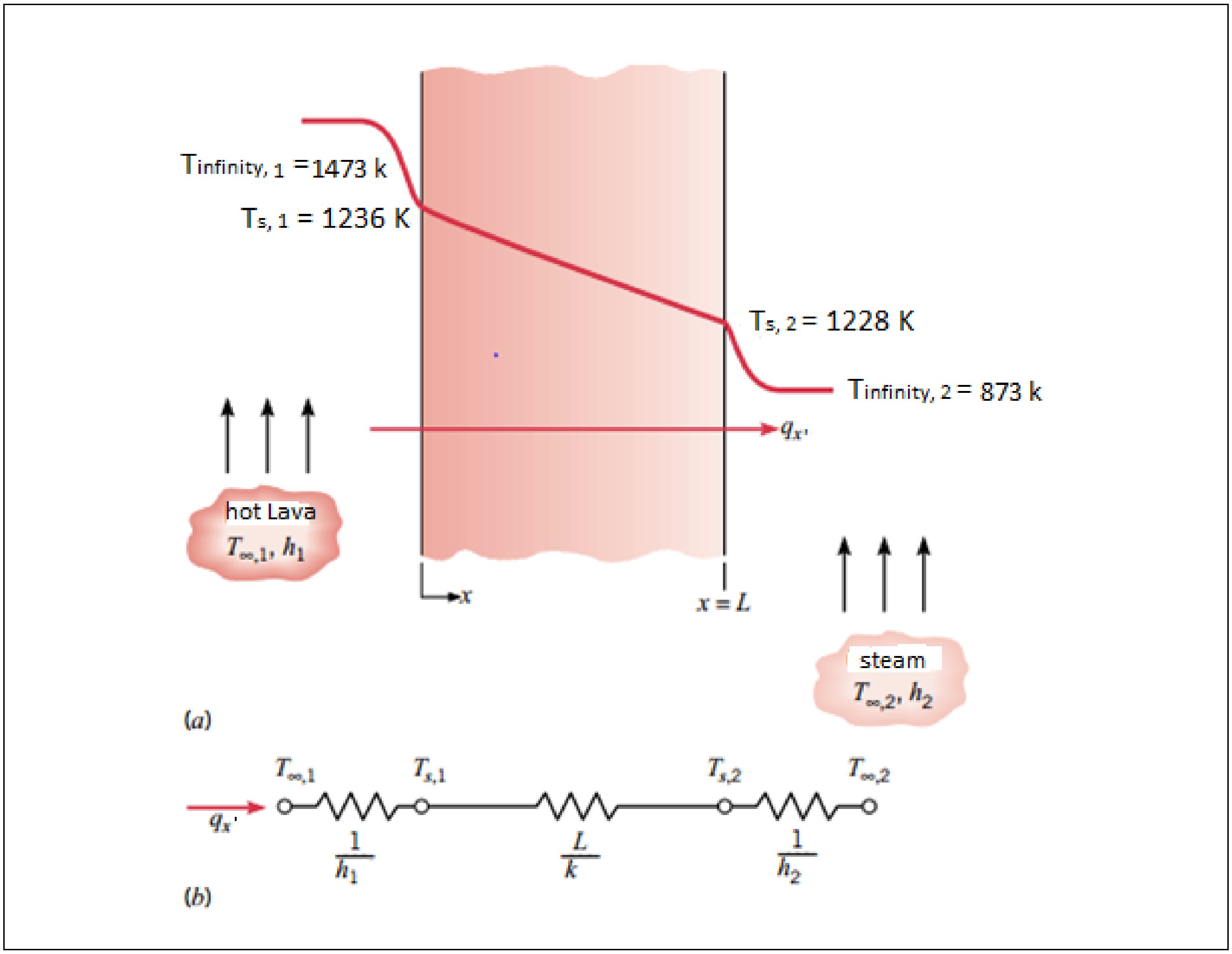


**Figure 5.1 Surface temperature for heat transfer per unit area through lake, steel and steam. (a) Temperature distribution. (b) Equivalent thermal circuit.**

Coating the pipe with brick can solve three main problems related to the study.

- Any body of steel pipe is exposed to a temperature less than 963 °C which enables the boiler to perform safely under high pressure of 180 bar. Its melting point is also reaches 1700 °C which kept overall system safe relative to high temperature 1200 °C.
- It will be used to keep temperature at a contact with liquid lava greater than 900 °C to avoid solidification.
- It also used to prevent corrosion of the pipe due to corrosive gases leaves the magma if there is a direct contact of pipe and lava fluid.

Brick has approximately melting point of 1780 $^{o}$C, thermo conductivity of 1.3 w/m.k and density of 2210 kg/m$^{3}$. After the pipe is coated by reinforced brick, heat transfer per unit area be become;

$$q_x' = (T_{\infty,1} - T_{\infty,2}) / (1/h_1) + (L_1/K_1) + (L_2/K_2) + (1/h_2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (5.9)$$

The temperature profile is calculated by;

$$q_x' = (T_{\infty,1} – T_{s,1}) / (1/h_1) = (T_{s,1} – T_{s,2}) / (L_1/K_1) = (T_{s,1} – T_{s,2}) / (L_2/K_2) = (T_{s,2} - T_{\infty,2}) / (1/h_2)$$

For constant *$T_{\infty}$ ,1 = 1473 K, $T_{\infty}$ ,2 = 873 K, $h_1$ = 140 W/m$^2$K, $h_2$ = 200 W/m$^2$K, $K_1$ = 30 W/m.K, $K_2$ = 1.3 W/m.K and $L_1$ = 0.00348 m value;*

**Table 5.2 Temperature at each surfaces of steal and brick with different brick thickness at temperature range of 873 K and 1473 K**

| t (m) | L1 (m) | L2 (m) | $q_x$'(w/m$^2$) | T s,1 | Ts,2 | Ts,3 |
|---|---|---|---|---|---|---|
| 0.001 | 0.00348 | 0.001 | 65086 | 1256 | 1248 | 1198 |
| 0.002 | 0.00348 | 0.002 | 60073 | 1273 | 1266 | 1173 |
| 0.003 | 0.00348 | 0.003 | 55778 | 1287 | 1281 | 1152 |
| 0.004 | 0.00348 | 0.004 | 52055 | 1299 | 1293 | 1133 |
| 0.005 | 0.00348 | 0.005 | 48798 | 1310 | 1305 | 1117 |
| 0.006 | 0.00348 | 0.006 | 45925 | 1320 | 1315 | 1103 |
| 0.007 | 0.00348 | 0.007 | 43372 | 1328 | 1323 | 1090 |
| 0.008 | 0.00348 | 0.008 | 41087 | 1336 | 1331 | 1078 |
| 0.009 | 0.00348 | 0.009 | 39031 | 1343 | 1338 | 1068 |
| 0.01 | 0.00348 | 0.01 | 37171 | 1349 | 1345 | 1059 |
| 0.015 | 0.00348 | 0.015 | 30018 | 1373 | 1369 | 1023 |
| 0.02 | 0.00348 | 0.02 | 25174 | 1389 | 1386 | 999 |
| 0.025 | 0.00348 | 0.025 | 21676 | 1401 | 1398 | 981 |
| 0.03 | 0.00348 | 0.03 | 19032 | 1410 | 1407 | 968 |
| 0.035 | 0.00348 | 0.035 | 16962 | 1416 | 1414 | 958 |
| 0.04 | 0.00348 | 0.04 | 15299 | 1422 | 1420 | 949 |
| 0.045 | 0.00348 | 0.045 | 13933 | 1427 | 1425 | 943 |
| 0.05 | 0.00348 | 0.05 | 12790 | 1430 | 1429 | 937 |

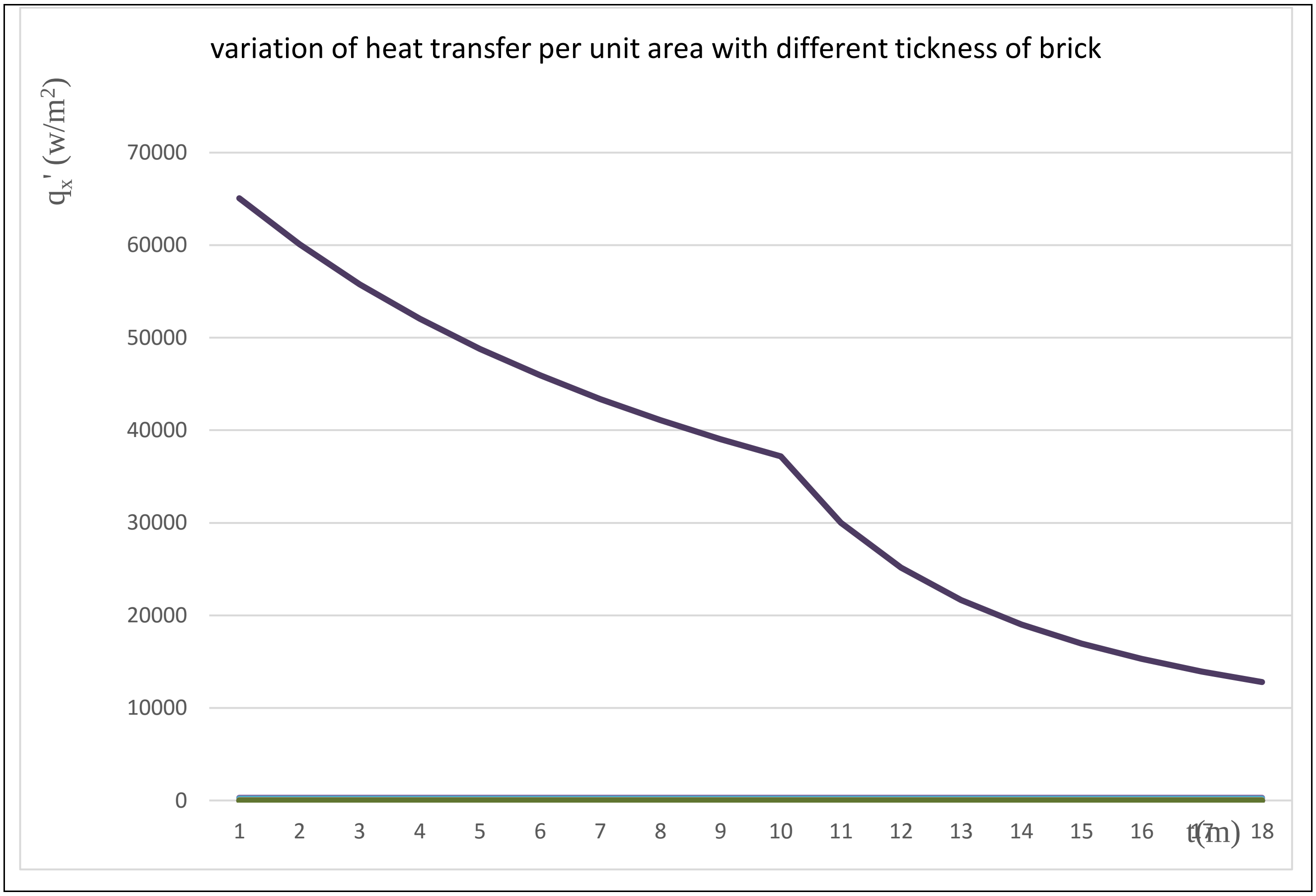


**Figure 5.2 Effect of thickness of brick on power**

Although it has a great advantage, if thickness of brick increases, heat transfer per unit area decreases steam boiler pipes. But for down comer, temperature inside the pipe falls to 319 K and thickness of brick is optimized to 15 mm and heat transfer per unit area become 57,735 W/m$^2$, $T_{\infty,1}$ is 1473 K (1200 $^oC$) and $T_{\infty,2}$ is 319 K (45.81 $^oC$). This is shown in Table 5.3.

This shows that, output power is inversely proportional to thickness of brick. But, for temperature adjustment criteria and constraint related to corrosion effect, the pipe must be coated with brick.

Temperature allowed at outside surface of the brick $T_{s,1}$ is greater than or equal to 1173 K or 900 °C. For instance, if t =1 mm, $q_x$' is 65,086 W/m$^2$ and $T_{s,1}$ is 1256 K, also if t =2 mm, $q_x$' is 60,073 W/m$^2$ and $T_{s,1}$ is 1272 K, and if t =3 mm, $q_x$' is 55'777 W/m$^2$ and $T_{s,1}$ is 1287 K.

This shows that, thickness of even 1mm is enough to satisfy our temperature requirement at outer surface 1173 K, because 1256 K (983 °C) is little bit greater than 1173 K (900 °C) for safe operation.

So, final optimized $T_{s,1}$ is 1256 K (983 °C) $T_{s,2}$ is 1248 K (975 °C) $T_{s,3}$ is 1198 K (925 $^0$C). Equivalent $q_x$' is 65,086 W/m$^2$, $T_{\infty,1}$ is 1473 K (1200 °C) and $T_{\infty,2}$ is 873 K (600 °C).

In general, at 983 °C, there is no possibility of condensation and at 975 °C, steel operate safely.

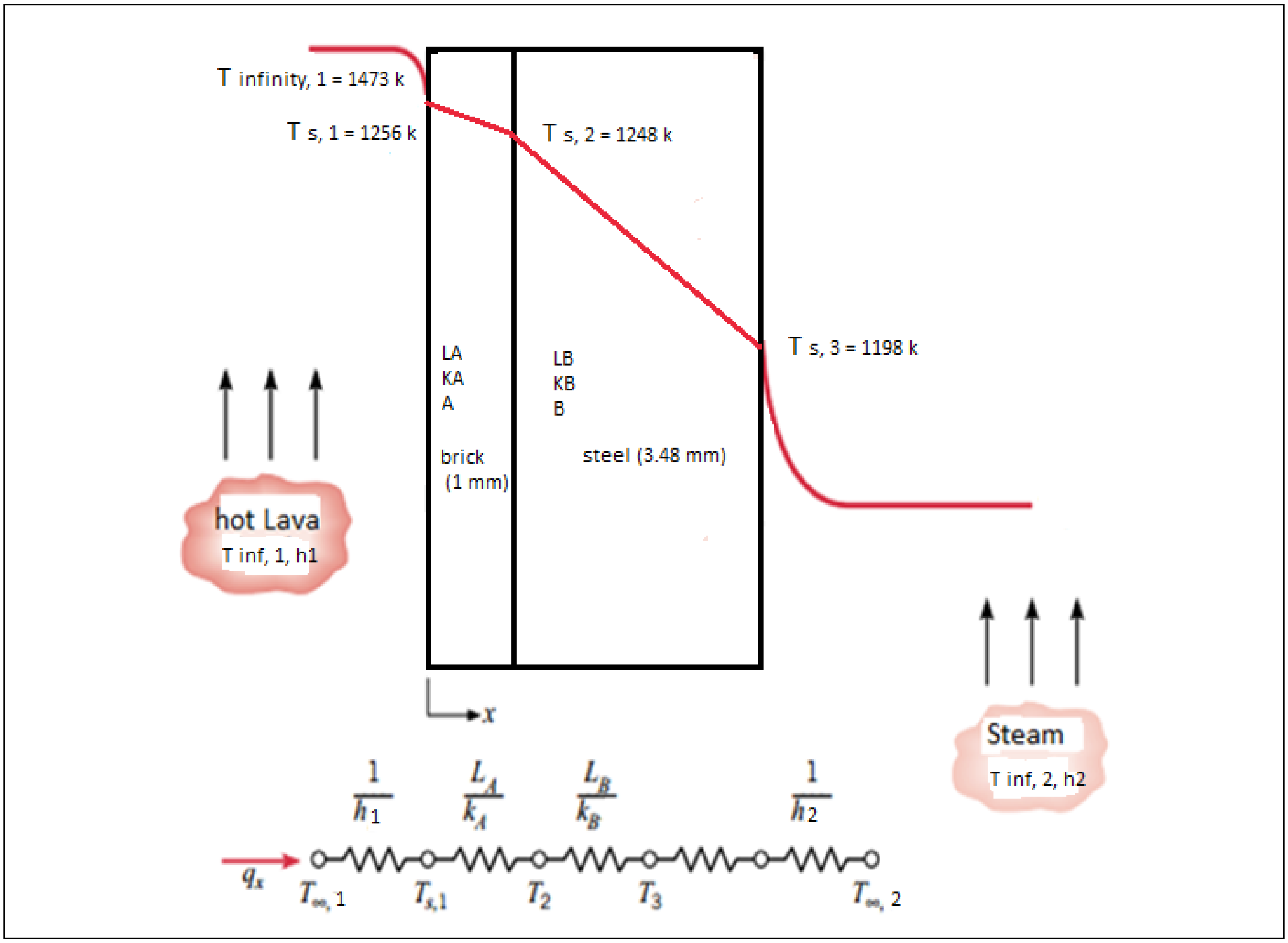


**Figure 5.3 Temperature distribution and Equivalent thermal circuit for lake, steel, brick and steam**

For down comer, temperature of steam inside the pipe ($T_{dc}$) is given by;

$$T_{dc} = T_{sat@Pcon} = T_{sat@10\ kpa} = 45.81\ ^{o}C$$

To keep the temperature outside the brick greater than 1256 K (983 $^{o}$C) to avoid solidification of lava and unwanted quenching effect, we shall optimize thickness of brick in the following table.

For constant $T_{\infty,1} = 1473$ K, $T_{\infty,2} = 319$ K, $h_1 = 140$ W/m$^2$K, $h_2 = 200$ W/m$^2$K, $K_1 = 30$ W/m.K, $K_2 = 1.3$ W/m.K and $L_1 = 0.00348$ m value;

**Table 5.3 Temperature at each surfaces of steal and brick with different brick thickness at 319 K and 1473 K**

| t (m) | L1 (m) | L2 (m) | qx' (w/m2) | T s,1 | Ts,2 | Ts,3 |
|---|---|---|---|---|---|---|
| 0.001 | 0.00348 | 0.001 | 125182 | 1056 | 1041 | 945 |
| 0.002 | 0.00348 | 0.002 | 115541 | 1088 | 1074 | 897 |
| 0.003 | 0.00348 | 0.003 | 107279 | 1115 | 1103 | 855 |
| 0.004 | 0.00348 | 0.004 | 100119 | 1139 | 1128 | 820 |
| 0.005 | 0.00348 | 0.005 | 93856 | 1160 | 1149 | 788 |
| 0.006 | 0.00348 | 0.006 | 88329 | 1179 | 1168 | 761 |
| 0.007 | 0.00348 | 0.007 | 83418 | 1195 | 1185 | 736 |
| 0.008 | 0.00348 | 0.008 | 79024 | 1210 | 1200 | 714 |
| 0.009 | 0.00348 | 0.009 | 75070 | 1223 | 1214 | 694 |
| 0.01 | 0.00348 | 0.01 | 71492 | 1235 | 1226 | 676 |
| 0.015 | 0.00348 | 0.015 | 57735 | 1281 | 1274 | 608 |
| 0.02 | 0.00348 | 0.02 | 48418 | 1312 | 1306 | 561 |
| 0.025 | 0.00348 | 0.025 | 41691 | 1334 | 1329 | 527 |
| 0.03 | 0.00348 | 0.03 | 36604 | 1351 | 1347 | 502 |
| 0.035 | 0.00348 | 0.035 | 32624 | 1364 | 1360 | 482 |
| 0.04 | 0.00348 | 0.04 | 29425 | 1375 | 1372 | 466 |
| 0.045 | 0.00348 | 0.045 | 26797 | 1384 | 1381 | 453 |
| 0.05 | 0.00348 | 0.05 | 24600 | 1391 | 1388 | 442 |

From the above table, optimal value of brick thickness is 0.015 m or 15 mm.

So, final optimized $T_{s,1}$ is 1281 K (1,008 $^{o}$C) $T_{s,2}$ is 1274 K (1,001 $^{o}$C) $T_{s,3}$ is 608 K (335 $^{0}$C). Equivalent $q_x$' is 57,735 W/m$^2$, $T_{\infty,1}$ is 1473 k (1200 $^{o}$C) and $T_{\infty,2}$ is 319 k (45.81 $^{o}$C) for this special type down comer. Although heat transfer per unit area is not much less than that of riser, it will be considered as negligible since number of riser is much greater than that of down comer.

## 5.3) Optimization of diameter of the pipes for maximum possible rate of heat transfer and fixing number of pipes

Different factors disallows us to use the whole area of the lake as it is;

- The place is a tourist place so that the nature and the shape of the lake shall not altered by human made phenomena.
- The solidified body, which has a very large mass and formed due to crystallinity of lava, may damage pipes if the whole area is occupied.
- The possibility of solidification of the lake is very high if the rate of heat transfer is too high through the whole area of the lake.
- Handling of pipes in space is more difficult than that of handling near the walls of the lake.

Due to the above constraints, the installation areas of the lake is limited to one layer around the perimeter of the lake. The perimeter of the lake is easily calculated by;

$$P = 2\pi r = 2\pi\left(\frac{\sqrt{A}}{\pi}\right) = 2\pi\left(\frac{\sqrt{6200}}{\pi}\right) = 280 \text{ m and radius (r)} = 44.5 \text{ m}$$

To optimize number of pipes required over this perimeter and for efficient heat transfer, Using standard Pipe diameter, with the range of 10mm to 1000mm, it is possible to calculate the diameter at which heat transfer rate per unit depth of pipe is maximum.

Assuming heat transfer through radial system, using thickness of pipe 3.48mm and thickness of brick 1 mm, at different diameters of pipe heat transfer per unit depth ($q_x''$) is shown in a table below.

$$q_x'' = (T_{\infty,1} - T_{\infty,4}) / (1/h_1A_{is}) + (1/2\pi K_1L_1) \ln (r_o/r_i) + (1/2\pi K_2L_2) \ln (r_o/r_i) + (1/h_2A_{ob}) \ldots\ldots.(5.10)$$

Estimating the exact value of power per unit depth of the lake is very difficult due to different errors during measurement of parameters and thermodynamic properties. This is not also the real power that will be extracted. This is power potential per unit depth. But actual power output is calculated by optimizing maximum possible length of pipes and considering overall thermal efficiency of the plant.

For constant $T_{\infty,1} = 1473$ K, $T_{\infty,2} = 873$ K, $h_1 = 140$ W/m$^2$K, $h_2 = 200$ W/m$^2$K, $K_1 = 30$ W/m.K, and $K_2 = 1.3$ W/m.K value;

**Table 5.4 Optimum rate of heat transfer per unit depth of the lake based on diameter of the brick coated pipe**

| D (m) | No pipes | $A_{ob}$ (m2) | qx'' (w/m) |
|---|---|---|---|
| 0.05 | 2,800 | 497 | 301,773,673 |
| 0.1 | 1,400 | 468 | 147,105,486 |
| 0.15 | 933 | 458 | 87,441,265 |
| 0.2 | 700 | 454 | 58,046,869 |
| 0.25 | 560 | 451 | 57,884,505 |
| 0.3 | 466 | 448 | 28,846,550 |
| 0.35 | 400 | 448 | 28,848,783 |
| 0.4 | 350 | 447 | 28,819,421 |
| 0.45 | 311 | 446 | 28,786,250 |
| 0.5 | 280 | 445 | 28,778,192 |
| 0.6 | 233 | 444 | 28,709,554 |
| 0.7 | 200 | 444 | 28,730,898 |
| 0.8 | 175 | 443 | 28,716,079 |
| 0.9 | 155 | 441 | 28,602,025 |
| 1 | 140 | 442 | 28,695,303 |

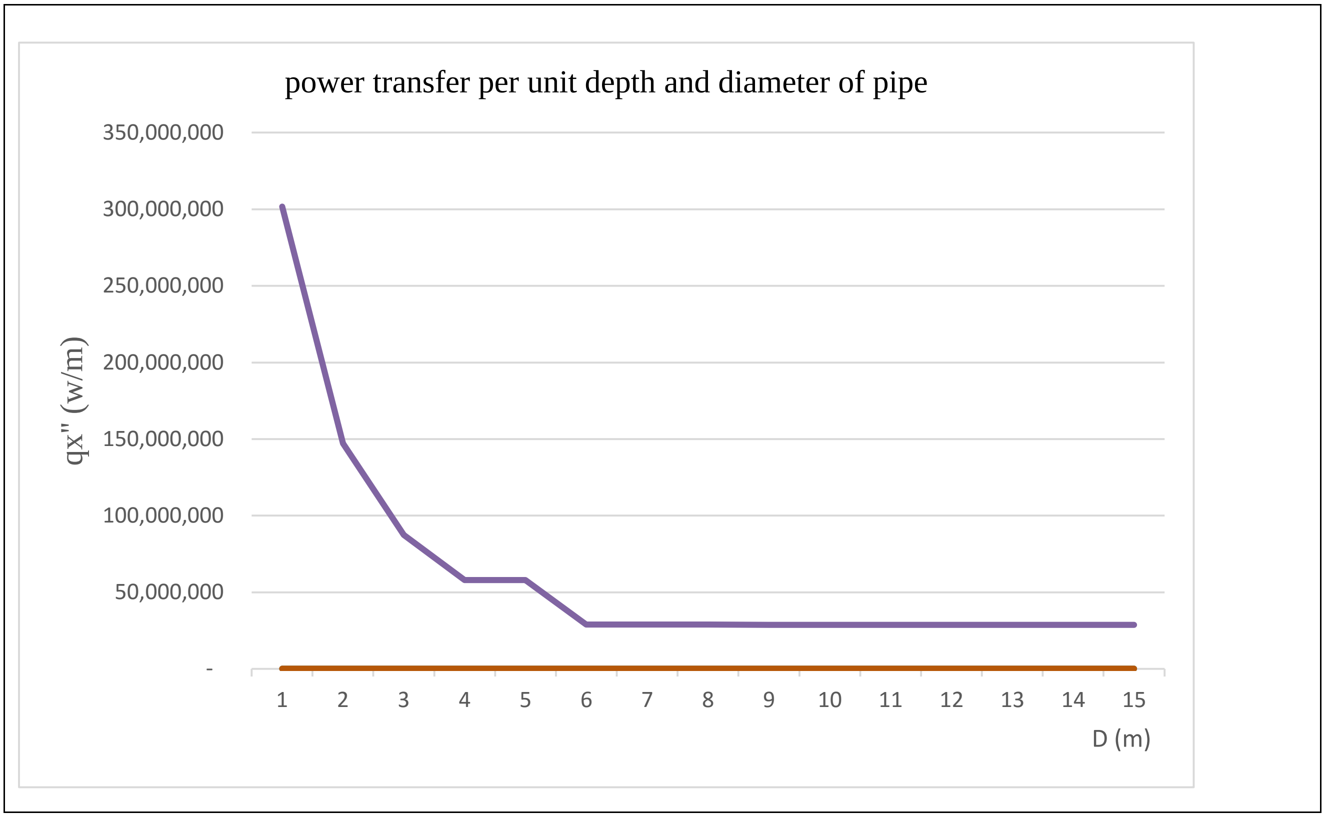


**Figure 5.4 Effect of diameter of pipe on power**

From the above table, as the diameter of the pipe decrease, the number of pipes and the rate of heat transfer per unit depth increases, within specified cross sectional area of the lake. But total output power depends on depth of pipes and convective heat transfer through total cross sectional area of the lake. This can be optimized in the next section.

## 5.4) Optimization of length of pipe with consideration of pressure gradient of lava along vertical axis and buoyance effect

It is obvious that as a length of pipe swallowed by the lake increases, the rate of heat transfer extremely increases. But, there were a constraints which limit the pipe length. Before analyzing the effect of those parameters it is important to consider the relationship between them in a table shown below. This is a relationship between heat transfer, external and internal pressure acting on a pipe and one most important parameter which completely affect operating condition of steam which is buoyancy effect.

### Table 5.5 Optimum rate of heat transfer per unit depth of the lake

| L (m) | Q (W) | Pout (bar) | Pin (bar) | $F_{bouyant}$ (KN) | $m_{ore}$ (Kg) | $m_{steel}$ (Kg) |
|---|---|---|---|---|---|---|
| 1 | 280,709 | 1.03 | 180 | 1,718 | 31,354 | 12 |
| 50 | 122,435,477 | 2.28 | 180 | 85,932 | 1,567,706 | 614 |
| 100 | 22,870,955 | 3.55 | 180 | 171,865 | 3,135,412 | 1,229 |
| 150 | 46,306,433 | 4.83 | 180 | 257,797 | 4,703,118 | 1,843 |
| 200 | 59,741,910 | 6.10 | 180 | 343,730 | 6,270,824 | 2,458 |
| 250 | 71,177,388 | 7.38 | 180 | 429,663 | 7,838,530 | 3,072 |
| 300 | 83,612,866 | 8.65 | 180 | 515,595 | 9,406,236 | 3,687 |
| 350 | 106,048,344 | 9.93 | 180 | 601,528 | 10,973,942 | 4,302 |
| 400 | 116,483,821 | 11.20 | 180 | 687,461 | 12,541,648 | 4,916 |
| 450 | 124,919,299 | 12.48 | 180 | 773,393 | 14,109,354 | 5,531 |
| 500 | 141,354,777 | 13.75 | 180 | 859,326 | 15,677,060 | 6,145 |
| 600 | 179,225,732 | 16.30 | 180 | 1,031,191 | 18,812,472 | 7,375 |
| 700 | 203,096,688 | 17.85 | 180 | 1,203,056 | 21,947,884 | 8,604 |
| 800 | 224,967,643 | 20.40 | 180 | 1,374,922 | 25,083,296 | 9,833 |
| 900 | 256,838,598 | 22.96 | 180 | 1,546,787 | 28,218,708 | 11,062 |
| 1000 | 283,709,554 | 25.51 | 180 | 1,718,652 | 31,354,120 | 12,291 |
| 1500 | 409,064,331 | 38.26 | 180 | 2,577,978 | 47,031,180 | 18,437 |
| 2000 | 576,419,108 | 51.01 | 180 | 3,437,305 | 62,708,240 | 24,583 |
| 3000 | 865,128,663 | 76.52 | 180 | 5,155,957 | 94,062,361 | 36,875 |

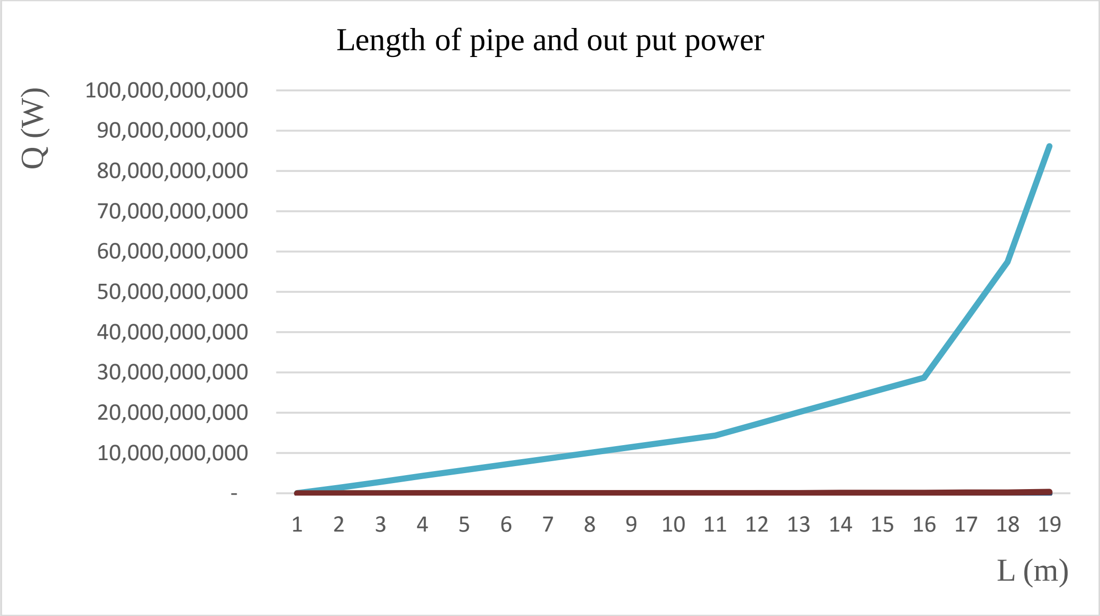


**Figure 5.5 Effect of depth of boiler pipe on power**

From the above table, four main cases that can be considered are;

- As a length of pipe increases, the rate of heat transfer increases by multiple of magnitude that added.
- The limited pressure in a pipe is 180 bar. The outside pressure exerted by fluid lava increases as depth or length of pipe increases and coincide with inside pressure inside pressure at the depth of approximately 800 m. At this point, pressure exerted by lava and steam is equal and cancel each other and pipe is assumed to be free of both tensile and compressive force. At 1500 m, outside pressure is almost twice inside pressure and since the steel can resist compressive stress which is the change in inside and outside pressure. But further increase in depth of insertion, require increase the thickness of the pipe.
- Operating depth more than 1500 m is very difficult during installation. Therefore, operating depth shall be optimized at the depth 1500 m for a given conditions.
- The main challenge to increase to increase the length of pipe is a buoyant force which tend to push the pipe upward and finally bend the pipe.

In general, the above four cases, shows that the buoyant force shall not strong enough to bend the pipe. The maximum compressive force of the steel pipe with a given dimension shall overcome the force acted by buoyancy effect. In addition to this, if the length of pipe exceeds 1500 m, it is very difficult to install the pipe in practice. As this problem is severe problem, which extremely affect the overall rate of heat transfer or power, it will require a possible solution. There are two possible suggested mechanisms which is relatively easier.

- As discussed earlier, decreasing diameter of pipes and increasing number of pipes in parallel, has another advantages in addition to increasing rate of heat transfer. Since density of steel is around 8000 kg/$m^3$ in comparison to that of lava around 3000 kg/$m^{3,}$ which is has density ratio of 3:1 shows that, diameter at which down ward and upward force coincide is given by;

  $\pi \text{ x } r_o^2/3 = \pi \text{ x } (r_o^2 - r_i^2)$ solving for diameter is 34 mm.

  Which could not feasible to exactly use but it is used to optimize the value.
- The most important solution that shall be consider in detail is to compensate high upward buoyant force, it is important to add heavy weight with the highest possible density or down ward force which compensate unwanted upward buoyant force. But type of material used to add weight shall fulfill the following three criteria's.
  - Temperature inside the lake (1473 K) is strong enough to melt most of materials. So the material that will be use shall have a melting point greater than (1473 K). For instance, melting point of most of stones are less than this temperature. But most of metals, ores and ceramics or clays has a high melting point.
  - Density of lava is estimated to be 3000 kg/$m^3$. But density of most of materials is less than this and density of most common materials are mentioned in Appendix E. But again density of steel is 8000 kg/$m^3$ which is approximately 3 times density of lava.
  - The third most important criteria which determine the possibility of this solving technique is cost of material that fulfill the above two criteria's. For instance, steel satisfy the first two criteria's but unfortunately fail the third criteria due to its high cost which is not feasible to use as extra material for weight.

In general, those three most important criteria's shows that, it is important to select the material which has;

- ✓ The highest possible melting point
- ✓ The highest possible density and
- ✓ The lowest possible cost

The material must fulfill this three criteria's and by giving equal value for those fulfillments we select the material which is called magnetite which has density of around 5200 kg/m$^3$ and cost of around 4 birr per kilogram. The mass of magnetite required to compensate the unwanted buoyant force is given in the above table.

Total power potential of this Lava Lake mainly depends on temperature difference between surface temperature of Moho and Lava fluid, contact area of Moho and Lava fluid and convective heat transfer coefficient of Lava.

Heat can transfer through the lava in a long lava tube from very high temperature rock inside the earth called Moho by convection, conduction and radiation. But convection heat transfer dominates conduction and radiation. So convection heat transfer was used and convection heat transfer coefficient was estimated as follows.

It is necessary to give ranges of values of h, of course, because h is not a true physical property. It is merely defined for given test conditions. The composition, velocity, viscosity of fluid, the temperature difference between the fluid and the surface, the surface roughness, temperature, and water content of the subsurface material (usually a solid but could be another fluid) affect the value of h though orders of magnitude. The following table shows values of h for common materials.

**Table 5.6 Heat transfer coefficients (h) for various test conditions [32]**

| Item no. | Fluid | Heat transfer coefficient (h) $(10^{-3}\ \text{cal})/(\text{cm}^2\ \text{d}^{\circ}\text{C})$ | Test conditions | References |
|---|---|---|---|---|
| 1 | Gases | 0.05 - 0.5 | free convection | Groeber 1961 |
| | water | 3 - 20 | do. | |
| | boiling water | 30 -500 | do. | |
| | gases | 0.3- 3 | forced convection | |
| | viscous liquids | 1 - 15 | do. | |
| | water | 15 -300 | do. | |
| | condensing steam | 30 -3000 | do. | |
| 2 | Water: distilled | 300 | (temp, near 50°C, veloc. 1-5 m/s, temp.diff. 1°-5°C) | Weber |
| | boiler feed | 150 | | |
| | brackish, river | 70 | | |
| | Muddy, Del. R. | 40 | | |
| | Chicago Sanitary | 15 | | |
| 3 | Water, Boiling | 3<br>15<br>25 | chromium pipe, flux: 0.05 HFU | Insinger and Bliss |
| 4 | Water | 20 -200 | quench of fused SiO2, and ceramic, at 900°C | Emery |
| 5 | Basalt lava, Kilauea | 1.12 | T=1088°C | Hardee |
| | | 2.54 | T = 1119°C | |
| 6 | Air, Ventilation | 0.6-0.72 | Phyllite | Barla and Mine |
| 7 | Air, ventilation | 0.1 – 10 | mine tunnel, dry | Danka and Cifka |
| | | 10 -50 | water evaporating | |

Converting 1.12 x $10^{-3}$ cal/cm$^2$ d$^o$C in to W/m$^2$K using conversion rate of 55 W/m$^2$K, h becomes 50 W/m$^2$K. Using surface temperature of Moho 1900 K, temperature of Lava at the surface of brick coated boiler 1256 K and assuming contact area of Moho and fluid lava equivalent to cross sectional area of the Lake,

$$P_t = h \times A \times \Delta T \quad \ldots\ldots (5.11)$$

$$P_t = 140\ W/m^2K \times 6{,}200\ m^2 \times (1{,}900\ K - 1{,}256\ K) = \mathbf{558{,}000{,}000\ W} \text{ or } \mathbf{558\ MW}$$

Average combined radiative and sensible heat losses to environment is estimated to 150 MW.

Ideal power potential of the Lake becomes;

$$P_{ideal} = P_t - P_{loss} = 558\ MW - 150\ MW = \mathbf{408\ MW}$$

This power is very low compared to maximum possible extractable power from this Lava Lake. Contact area of surface of Moho and Lava is relatively much larger than area of the lake as shown in figure 5.5. But, in this case it is assumed to be equivalent to cross sectional area of the lake.

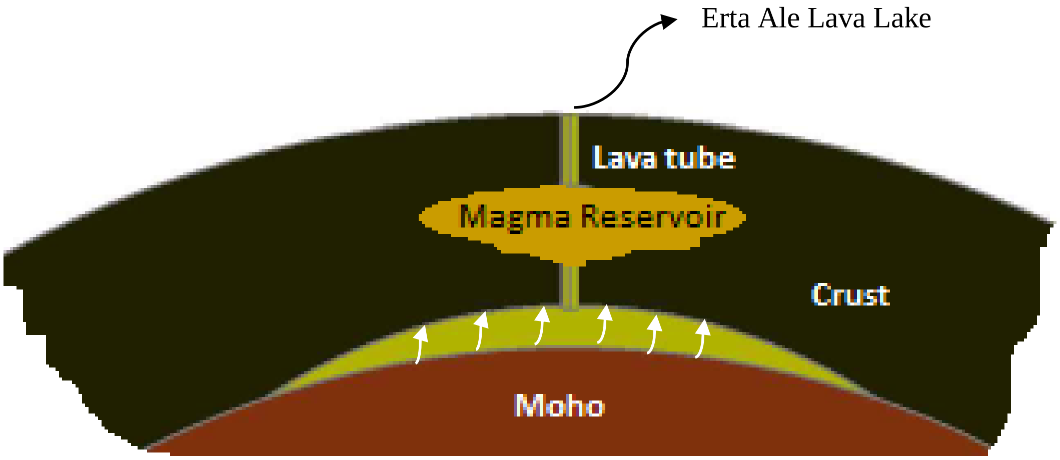


**Figure 5.6 Model of Lava Tube and Magma Reservoir**

From table 5.4, if the commonly available diameter of pipe 600 mm is selected, power per unit depth of single pipe is 123,216 W/m. Power per single pipe ($P_s$) become;

$$P_s = 123{,}216\ W/m \times 1500\ m = \mathbf{184{,}824{,}000\ W = 184.82\ MW}$$

- Total number of pipe ($N_{pt}$) = 408 MW / 184.82 MW = **2.2 ≈ 3**

## 5.5) Estimation of power potential of Erta Ale Lava Lake

To end up the estimation of power potential, there are different procedural calculations and estimations of different hardware variables especially that related to steam generator or boiler. To estimate final out put power it is important first to estimate the rate of heat transfer to boiler depending on the parameters optimized in the first part of this chapter. Ideal power potential is equivalent to heat transfer to boiler ($\mathbf{Q_{boiler}}$);

$$\mathbf{Q_{boiler} = 408{,}000{,}000\ W \quad or \quad 408\ MW.}$$

Using this value as a reference, it is important to use energy balance equation to calculate energy analysis in different components of power plants. By calculating overall efficiency of the plant, the final power output can also be calculated.

Based on operating parameters of modern power plants, by fixing or assuming;

- Boiler pressure 180 bar
- Condenser pressure 10 kPa
- Turbine inlet temperature 560 $^{o}$C
- Minimum pump efficiency 0.95
- Minimum turbine efficiency 0.9
- Minimum generator efficiency 0.95

Some basic assumptions are;

- Steady flow process
- Kinetic and potential energy changes are negligible
- Steam leaves the condenser and enters the pump as saturated liquid at condenser pressure

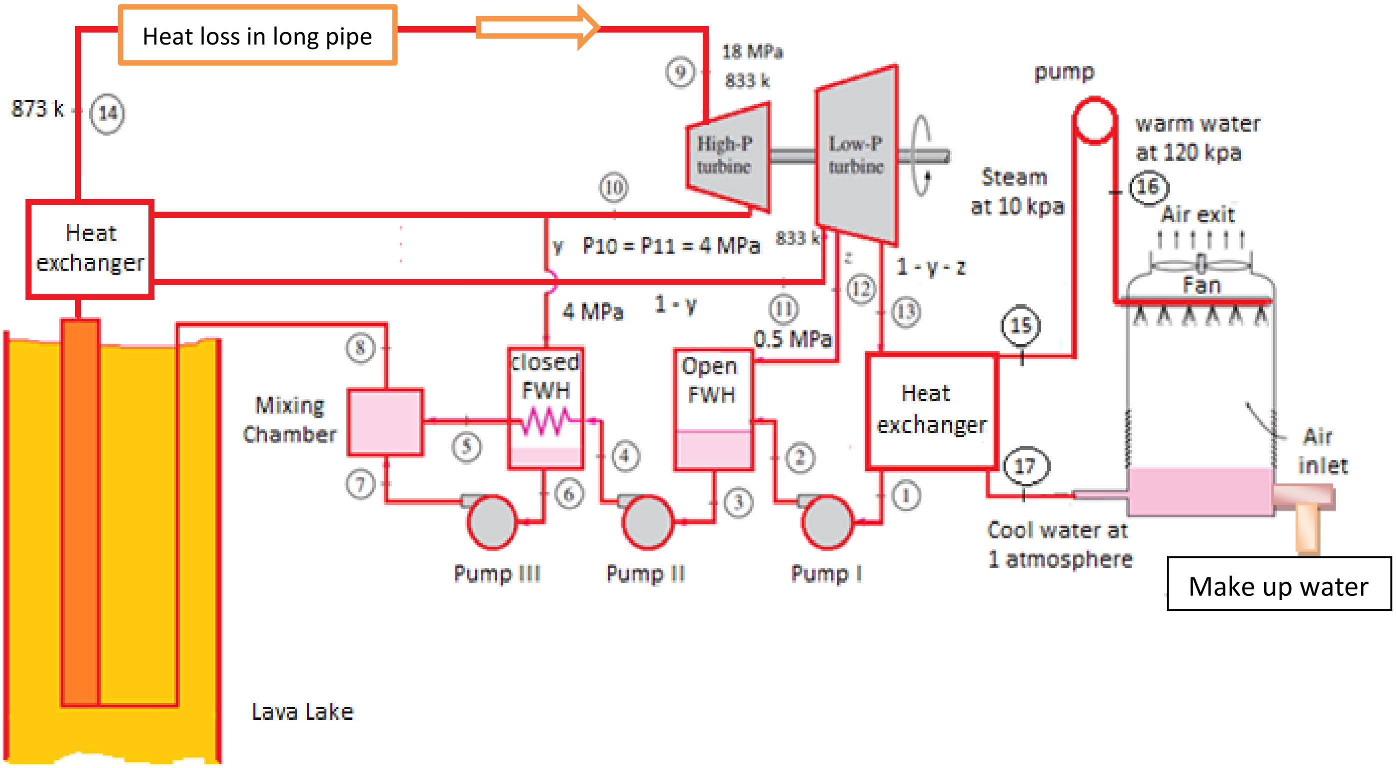


Figure 5.7 Layout of the plant

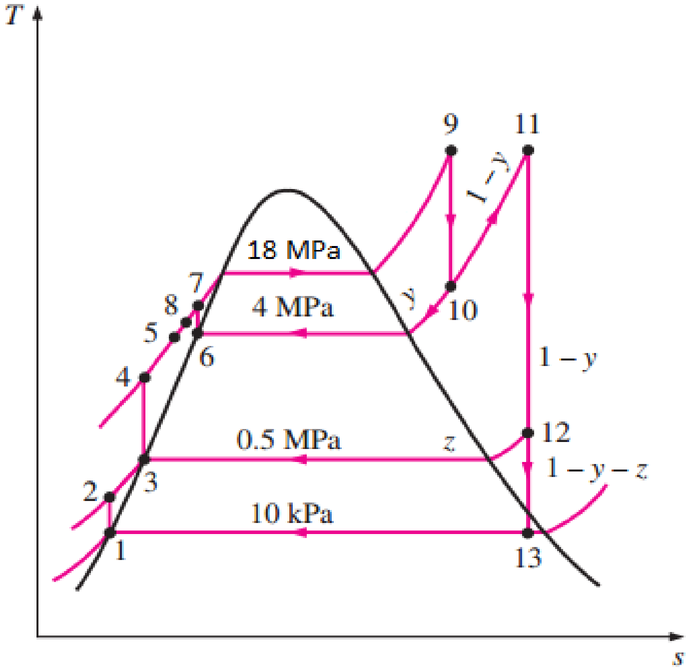


Figure 5.8 T-S diagram of the plant

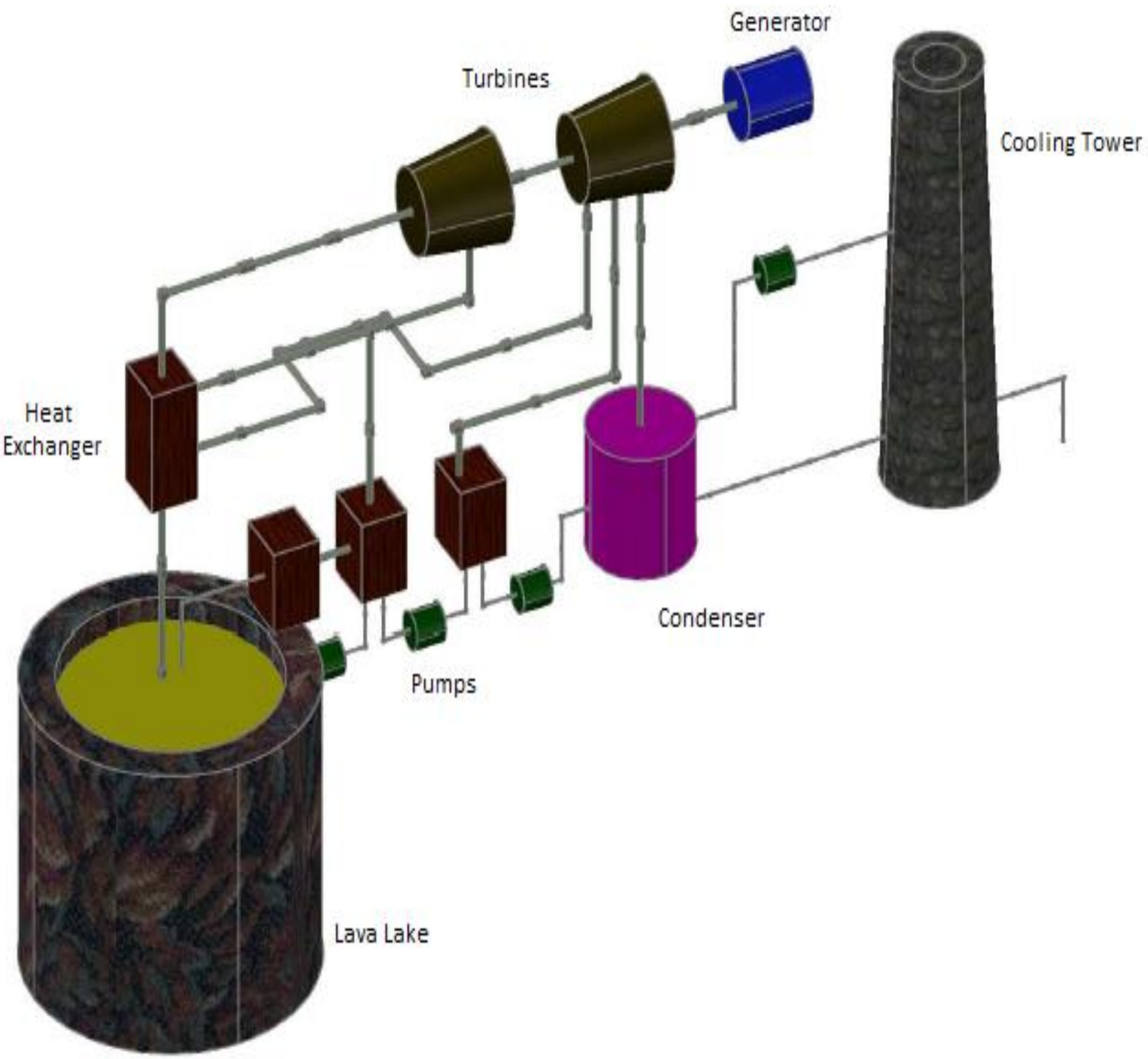


**Figure 5.9 3D model of the plant**

To check the phase of steam at 560 $^oC$ and 180 bar or 18 MPa from steam table in appendix B

$T_{sat@18\ MPa} = 356.99\ ^oC$

This clearly shows that, $T_{sat} = 356.99\ ^oC < 560\ ^oC$.

This shows that phase of steam at the inlet of the turbine is super-heated steam.

- Work of pump I

Assuming efficiency of pump 0.9,

**State 1**; @ $P_1$ = 10 kPa and saturated liquid phase, from steam table in appendix B

$h_1 = h_{f@10\ kpa} = 191.81$ kJ/kg

$v_1 = v_{f@10\ kpa} = 0.000101$ kg/m$^3$

**State 2**; Assuming a pressure for the open feed water heater 0.5 MPa and specific volume of water before and after pump is equal, $v_2 = v_1$

@$P_2$ = 0.5 MPa and $S_1 = S_2$

$W_{s,pump}$ I= $h_2 - h_1 = v_1 (p_2 - P_1)$

0.00101 kg/m$^3$ x [(500-10) kPa]x(1 kJ/1 kPa.m$^3$) = 0.5 kJ/kg

$W_{a,pump}$ I= $W_{s,pump}$ I / 0.9 = 0.55 kJ/kg

$h_2 = h_1 + W_{a,pump}$, I and $h_2$ = 191.81 kJ/kg + 0.55 kJ/kg = 192.36 kJ/kg

**State 3**; @ $P_3$ = 0.5 MPa and saturated liquid, from steam table in appendix B

$h_3 = h_{f@10\ kpa} = 640.09$ kJ/kg

$v_3 = v_{f@10\ kpa} = 0.001093$ kg/m$^3$

**State 4**; @ $P_4$ = 18 MPa and $s_3 = s_4$, from steam table in appendix B

$h_4 = h_{f@10\ kpa} = 640.09$ kJ/kg

$v_4 = v_{f@10\ kpa} = 0.001093\ kg/m^3$

$W_{s,pump}\ II = h_4 – h_3 = v_3\ (P_4 – P_3)$

$0.001093\ kg/\ m^3 \times [(18000\text{-}500)\ kPa] \times (1\ kJ/1\ kPa.m^3) = 19.13\ kJ/kg$

$W_{a,pump}\ II = W_{s,pump}\ II\ /\ 0.9 = 21.25\ kJ/kg$

$h_4 = h_3 + W_{a,pump}$, II and $h_4 = 640.09\ kJ/kg + 21.25\ kJ/kg = 661.34\ kJ/kg$

**State 9**; @ $P_9$ = 18 MPa and $T_9$ = 560 °C, from steam table in appendix C

$h_9$ = 3456 kJ/kg and

$S_9$ = 6.4433 kJ/kg.K, (by double interpolation)

Assuming $S_9 = S_{10}$, to check the phase of steam at $S_{10}$ = 6.4433 kJ/kg.K and 4 MPa from steam table in appendix B

$S_{g@4\ MPa} = 6.0699$ kJ/kg.K.

This clearly shows that, $S_g = 6.0699 < 6.4433$ kJ/kg.K.

So, phase of steam at the inlet of the closed FWH is super-heated steam.

**State 10**; @ $P_{10}$ = 4 MPa and $S_{10}$ = 6.4433 kJ/kg.K, from steam table in appendix C

$h_{10}$ = 3021 kJ/kg and

$T_{10}$ = 322 °C (by linear interpolation)

In both open and closed feed water heaters, feed water is heated to the saturation temperature at the feed water heater pressure. (Note that this is a conservative assumption since extracted steam enters the closed feed water heater at 322 °C and the saturation temperature at the closed feed water pressure of 4 MPa is 250°C). From this state 5 became,

**State 5**; @ $P_5$ = 18 MPa and $T_5$ = 250 °C, from steam table in appendix A

$h_5 = h_{f@250\ ^oC} + v_{f@250\ ^oC}\ (P – P_{sat})$

$= 1085.7$ kJ/kg + 0.001252 kg/m$^3$ (4000 – 3976) kPa = 1085.73kJ/kg

$v_5 = v_{f@250\,^oC} = 0.001252$ kg/m$^3$

**State 6**; @ $P_6$ = 4 MPa and saturated liquid, from steam table in appendix B

$h_6 = h_{f@4\,MPa} = 1085$ KJ/Kg

$v_6 = v_{f@4\,MPa} = 0.001252$ Kg/m$^3$

$T_6 = 250$ $^o$C

**State 7**; Assuming a pressure for the closed feed water heater 4 MPa and specific volume of water before and after pump is equal, $v_7 = v_6$

@$P_6$ = 4 MPa and $S_6 = S_7$

$W_{s,pump}$ III= $h_7 – h_6 = v_6 (p_7 – P_6)$

0.001252 kg/m$^3$ x [(18000-4000) kPa]x(1 kJ/1 kPa.m$^3$) = 17.528 kJ/kg

$W_{a,pump}$ III= $W_{s,pump}$ III / 0.9 = 19.47 kJ/kg

$h_7 = h_6 + W_{a,pump}$, III and $h_7$ = 1085 kJ/kg + 19.47 kJ/kg = 1104.47 kJ/kg

**State 11**; @ $P_{11}$ = 4 MPa and $T_{11}$ = 560 $^o$C, from steam table in appendix C

$h_{11}$ = 3583 kJ/kg and

$S_{11}$ = 7.2350 kJ/kg.K, (by linear interpolation)

Assuming $S_{11} = S_{12}$, to check the phase of steam at $S_{12}$ = 7.2350 kJ/kg.K and 0.5 MPa from steam table in appendix B

$S_{g@0.5\,MPa} = 6.8207$ kJ/kg.K.

This clearly shows that, $S_g = 6.8207 < 7.2350$ kJ/kg.K.

So, phase of steam at the inlet of the open FWH is super-heated steam.

**State 12**; @ $P_{12}$ = 0.5 MPa and $S_{12}$ = 7.2350 kJ/kg.K, from steam table in appendix C

$h_{12}$ = 2958 kJ/kg and

$T_{12}$ = 248 $^oC$ (by linear interpolation)

**State 13;** Assuming $S_{12} = S_{13}$, to check the phase of steam at $S_{13}$ = 7.2350 kJ/kg.K and 10 KPa from steam table in appendix B

$S_{g@0.5\ MPa}$ = 8.1488 kJ/kg.K

This clearly shows that, $S_g$ =8.1488 kJ/kg.K > 7.2350 kJ/kg.K.

So, phase of steam at the inlet of the condenser is saturated mixture.

@$P_{13}$ = 10 KPa and $S_{13}$ = 7.2350 kJ/kg.K, from steam table in appendix B

$h_f$ = 191.81 kJ/kg and $h_{fg}$= 2392 kJ/kg

$S_f$ = 0.6492 kJ/kg.K and $S_{fg}$ = 7.4996 kJ/kg.K

$T_{sat}$ = 45.81 $^oC$

$X_{13} = (S_{13} – S_f) / S_{fg}$ = (7.2350 kJ/kg.K - 0.6492 kJ/kg.K) / 7.4996 kJ/kg.K = 0.88

$h_{13} = h_f + X\ h_{fg}$ = 191.81 kJ/kg + 0.88 x 2392 kJ/kg = 2296.77 kJ/kg

**State 8;** the fractions of steam extracted are determined from the mass and energy balances of the feed water heaters:

**Closed feed water heater:**

$$E_{in} = E_{out}$$

$$yh_{10} + (1-y)\ h_4 = (1-y)\ h_5 + yh_6$$

$$y = (h_5 – h_4) / (h_{10} – h_6) + (h_5 – h_4) = (1085 – 640) / (3021 – 1085) + (1085 – 640) = 0.187$$

**Open feed water heater:**

$$E_{in} = E_{out}$$

$$zh_{12} + (1\text{-}y\text{-}z)\ h_2 = (1\text{-}y)\ h_3$$

$$z = [(1\text{-}y)\ (h_3 - h_2)] / (h_{12}\text{-}h_2) = [(1\text{-}\ 0.187)\ (640 – 192)] / (2958 – 192) = 0.132$$

The enthalpy at state 8 is determined by applying the mass and energy equations to the mixing chamber, which is assumed to be insulated:

$$E_{in} = E_{out}$$

$$(1)\ h_8 = (1\text{-}y)\ h_5 + yh_7$$

$$h_8 = (1\text{-}y)\ h_5 + y\ h_7$$

$$h_8 = (1\text{-}0.187)\ 1085 + 0.187 \times 1104 = 1088.448\ \text{kJ/kg}$$

**State 14**; heat loss and friction loss, from steam table in appendix C

@ $P_{14} = 18$ MPa and $T_{14} = 600\ ^oC$,

$h_{14} = 3560$ kJ/kg

The turbine shall approximately 100 m far away from the edge of the lake due to high temperature around the lake and in addition to this surface of the lake is far away around 80 m from the edge of the lake. Due to this reason temperature of the steam in a boiler pipe approximately reduces from 873 K to 833 K.

- Turbine work

$W_{turbine\ out} = (h_9 – h_{10}) + (1\text{-}y)\ (h_{11} – h_{12}) + (1 – y – z)\ (h_{12} – h_{13})$

$= (3456 – 3021) + (1 – 0.187)\ (3583 - 2958) + (1 – 0.187 - 0.132)\ (2958 – 2297)$

$= 1393$ kJ/kg

- Heat loss ($H_{loss}$)

$H_{loss} = h_{14} – h_9$ = 3560 kJ/kg – 3456 kJ/kg = 104 kJ/kg

This shows that, it is very low when we compare it with principal turbine work.

- Pump work

$W_{pump\ in} = (1 – y – z)\ W_{pump\ in}\ I + (1 – y)\ W_{pump\ in}\ II + (y)\ W_{pump\ in}\ III$

$= (1 – 0.187 – 0.132)\ 0.55 + (1 – 0.187)\ 21.15 + (0.187)\ 19.47$

$= 21.21$ kJ/kg

But in this special power plant, the water at the end of down comer which has a depth of 1500 m, fluid pressure due to gravity become;

$P_f = \rho \times g \times h = 1000\ kg/m^3 \times 10\ m/s^2 \times 1500\ m = 15{,}000{,}000\ Pa$ or 150 bar

Due to this reason, the pump must rise pressure up to only 30 bar to avoid over pressure in boiler pipes and reduce pump work. This is only 16.6 % of total required pump work to rise pressure to 180 bar,

Which is 21.21 kJ/kg x 0.166 = 3.535 kJ/kg, which is actual pump work

The reduction in pump work is (21.21 – 3.535) kJ/kg is 17.675 kJ/kg

In other word, this means that pump II and pump III must not exceed pressure greater 4 Mpa.

- In put heat

$q_{in} = (h_{14} – h_8) + (1-y)\ (h_{11} – h_1)$

$= (3560 – 1088) + (1 – 0.187)\ (3583 – 3021) = 2928.9$ KJ/Kg

- Output heat

$q_{out\ 1} = (1-y-z)\ (h_{13} - h_{10}) + 104$ kJ/kg

$= (1-0.187-0.132)\ (2297 - 192) = 1537$ kJ/kg

But, due to advantage obtained from reduction of pump work, output heat is reduced to;

$q_{out}$ = 1433 kJ/kg - 17.675 kJ/kg = 1519.3 kJ/kg

- Thermal efficiency ($\eta_{th}$)

$\eta_{th} = 1 - (q_{out} / q_{in}) = 1 - (1519.3$ kJ/kg / 2928.9 kJ/kg) = 0.492 or **49.2 %.**

- Mass flow rate of steam

$m_s = Q_{in} / q_{in}$ = 408,000,000 W / 2,928,900 J/kg = 139.3 kg/s

- Net power output become

$P_{net}$ = Qin x $\eta_{th}$ = 408,000,000 J/s x 0.492 = 200,736,000 w

= **200.7 MW**

- Number of Turbines units ($N_{tu}$)

It is possible to use one standard turbine which has a capacity of 200 MW

- Speed of steam in a boiler pipe ($V_s$) is given by;

First mass flow rate of steam per one pipe ($m_{sp}$) is;

$m_{sp} = m_s / N_t$ = 139.3 kg/s / 3 = **46.3 kg/s** and to calculate speed of steam, first calculate

$m_{sp} = \rho \times V_{st} = 1/v_{@600\,^oC} \times V_{st}$ this implies that volume flow rate of steam per pipe is;

$V_{st}$ = (46.3 kg/s) / (1 / 0.0204954 $m^3$/kg) = **1.045 $m^3$/s**

Speed of steam in a turbine, $V_s$ becomes;

$V_s = V_{st}$ / (3.14 x 0.3 x 0.3) = **6.697 m/s** which is safe under given condition.

- Diameter of down comers ($D_d$) is given by;

$A_d = A_r \times (v_{water} / v_{steam})$ = 3.14 x 90000 x (0.001 / 0.0204954) = **13,795 $mm^2$**

**$D_d$ = 132 mm**

- Mass flow rate of water in cooling tower ($m_w$)

First of all, $T_{sat@10kpa}$ is 45.81 $^oC$. This a condenser temperature. Assuming temperature of cooling water 35 $^oC$ and 45 $^oC$ at the inlet and exit of the condenser, mass flow rate of cooling water becomes;

$m_s (h_{13} – h_1) = m_w (Cp\ \Delta T)$ and

$m_w$ = [(2296 – 191) kJ/kg x (139 kg/s)] / (4.22 kJ/kg.K x (45 – 35 $^oC$)) = **6,933 kg/s**

Assuming ambient temperature 30 $^oC$ and wet bulb temperature of 20 $^oC$, for the air at a given environment. Also assuming temperature and relative humidity at the exit of cooling tower 40 $^oC$ and 90 %, respectively.

Mass flow rate of air ($m_a$) in cooling tower is determined by;

$m_a = [m_w (h_{15} - h_{17})] / [(h_{exit} - h_{inlet}) - (\omega_{exit} - \omega_{exit}) h_{17}]$, but from psychometric chart in Appendix G;

$m_a$ = [6,933 x (188.44 – 146.64)] / [(150 - 58) - (0.045 – 0.001) x 146.64] = **3,389 kg/s**

- To calculate mass flow rate of make-up water ($m_{wmakeup}$);

$m_{wmakeup} = m_a (\omega_{exit} - \omega_{exit})$ = 3,389 kg/s x (0.045 – 0.001) = **149 kg/s**

An optimized net power out put 200 MW is relatively very low when compared with maximum possible extractable power from the lake. Total source of energy is assumed to be infinity if compared with this value. But the constraint that affect extraction of maximum power from this lake is ways of heat transfer through several kilometers.

Heat can transfer through the lake in a long lava tube from relatively very high surface temperature inside the earth called moho by convection, conduction and radiation. But convection heat transfer dominates conduction and radiation. Conduction heat transfer in this case based on low thermo conductivity of lava approximately 1 W/mK and long depth around 2800 km increases thermal resistivity. Radiation heat transfer is also relatively very low in liquid. So, convection heat transfer equation was used, with low heat transfer coefficient of lava 50 $W/m^2 K$.

The contact area of fluid lava with surface of high temperature moho that has been considered in this work is minimum area that is equivalent to actual area of the lake. But contact area of lava fluid with moho is much greater than this value. This shows that there is high possibility of increasing amount of power that has already been optimized in this work.

Temperature at each surface of brick coated steam boiler has been optimized by adjusting thickness of steel pipe and brick. Even though it is possible to use thousands of pipes to extract large amount of power, only 3 pipes with diameter and length of 0.6 m and 1500 m was enough required out put power. Log Mean Temperature Difference (LMTD) equation can be used to calculate heat transfer in different types of heat exchangers. But, in this case, length of pipe is extremely very long and due to this reason, Log Mean Temperature Difference (LMTD) is almost similar to Arithmetic Mean Temperature Difference (AMTD). So temperature difference between lava and steam has been directly used.

After completing optimization of parameters of brick coated heat exchanger and calculation of heat transfer to steam, it is very easy to calculate entire parameters using conventional vapor power plant design. Turbine of this power plant far approximately 180 m from brick coated steam boiler. Temperature drop due to heat loss in pipe and fluid friction has been considered. Temperature pof steam inside brick coated boiler is approximately 600 $^oC$. But, temperature at the inlet of turbine approximately dropped to 560 $^oC$ due to those losses.

# Chapter Six

## 6) Conclusion and Recommendation

### 6.1) Conclusion

The aim of this study is primarily based on two separate tasks which are assessing full energy potential and generation of 200 MW electricity. It require the great effort and procedural scientific methods through challenging optimization works to realize those aims. But, it is obvious as energy is one of the most essential element for human activities and this could create a great chance to reduce scarcity of national energy supply.

Calculation based on a scientific reality using discretization in to shells clearly shows that, an internal heat content of our planet was estimated to be $10^{31}$ joules. General assumptions based on different characteristics and formation of Erta Ale Lava Lake also clearly shows that, this lake was a result of pulling apart of three tectonic and the divergent force allows the lake continuously active or the flowing lava is directly joined with the mantle of the earth through magma tube magma reservoir. In general, from this shows that through convection heat transfer, due to increasing thermal gradient by pressure difference through the depth of the earth, it is really possible to extract heat using any type heat exchanger device and working fluid less than 1200 $^{o}$C from this Lava Lake.

Obviously, steam boiler transfer heat from any kind of source regardless of whether it is a coal fire, nuclear reactor and hot Lava. Any kind of steam turbine convert heat from any kind of using temperature of steam around 560 $^{o}$C to electrical energy. Maximum recorded magma temperature is about 1200 $^{o}$C and thermal gradient through 1500 m is almost negligible. Melting point of steel which is used as most of common steam boilers is 1425 $^{o}$C and greater than this maximum Lava temperature. This clearly shows that, there is no any possibility of melting of steel. But the main thing that shall be considered here is that at 1200 $^{o}$C it is difficult to withstand boiler pressure around 180 bar. Other severe problem which cause headache on a design of this special type steam generator is condensation of lava at a temperature less than 1000 $^{o}$C. So, for safe operating condition, an optimized temperature becomes 975 $^{o}$C at the surface of the steel and 983 $^{o}$C at outer most surface of the brick. To optimize a temperature based on those constraints and avoid corrosion, it is required to coat a steam boiler by brick.

In general, from the above mentioned facts and processes, there is a possibility of generation of electricity from Lava Lake using special design of brick coated steam boiler. But the main task is ways of extraction of maximum possible power from this Lava Lake. To optimize different parameters and thermodynamic properties we conclude that;

- Thickness of brick is inversely proportional to heat transfer per unit area.
- Diameter of boiler pipe is inversely proportional to heat transfer per unit depth and number of pipes.
- Length or depth of pipe is directly proportional to overall power output of from the lake.
- The effect of upward buoyant force require large mass of magnetite through the depth of the Lava Lake.
- The compressive force due to pressure gradient that crush boiler pipes increases and reach at severe level at the depth of 1500 m.

## 6.2) Recommendation

The possibility of extraction of power from Erta Ale Lava Lake natural gift was exactly realized through great effort using scientific facts and creative ways beyond expectation. But, there is a great deference between an ideal possibility and real possibility. The dream related to ideal possibility was already achieved in this work. But the dream related to real possibility will require a recommendation of the rest works specially issues related to budget constraint, feasibility, consultation, etc. Based on conclusion in this thesis work, recommendation to whom it concerns, are as follows;

- The scenario of characteristics of this Lava Lake shall give attention and studied in extreme detail.
- Temperature profile at Lava Lake along vertical direction must be studied and analyzed in extreme detail and modified if necessary.
- Hazardous catastrophes related to volcanic eruption which totally destroy the plant shall properly determine.
- The repetitive and successful optimization shall be done on operating performance of boiler pipe at 1200 $^{o}$C in extreme detail and re optimize if there is any failure condition. Based on sophisticated experimental and design analysis in relative to modern heat exchanger

technologies, thickness of boiler pipe the brick shall be carefully determined. If possible, it is required to change boiler materials using other alternatives.

- By considering special thermodynamic properties of fluid Lava, it is required to exactly calculate and test the rate of heat transfer and coefficient of convective heat transfer as well as crystallization and solidification of lava.
- Temperature profile at the surface of steal and brick must be checked experimentally in extreme detail and corrected if needed.
- Through experimental and careful design, depth of the lake, diameter of pipes and space between them must be re optimized and modify parameters if necessary.
- To avoid buoyancy effect, it is required to replace the cheapest material than magnetite if possible. It is also possible to create other simple solution to replace this suggested mechanism.
- Simulation of this special type power plant is very difficult using common software’s like Thermo Flex and Ansyis. So, it is very important to develop a new software to properly simulate this system.
- Similar to any power plant system, feasibility study is very important to realize the dream of generation of electricity from this Lava Lake.
- Scientists realized that the core of the earth has abundant heavy and expensive elements such as Iron, Gold and Uranium. Using this opportunity to reach the core of the earth through liquid phase, there could be a situation to invent easy way to extract those plenty of Iron, Gold and Uranium.
- The exact information about contact area of fluid lava and high temperature moho on which convective heat transfer depend shall properly studied.
- Finally, it is very important to design air conditioning system in the area during installation of this power plant.

## References

[1] Davies, J. H., & Davies, D. R. (2010). Earth's surface heat flux. Solid Earth.

[2] Turcotte, D. L., & Schubert, G. (2002). Geodynamics. Cambridge University Press.

[3] Fridleifsson, B., Bertani, R., (2008). Earth’s temperature. Ladislaus.

[4] Buffett, B. A. (2007). Taking earth's temperature. Science, 315(5820), 1801–1802.

[5] Archer, D. (2012). Global Warming: Understanding the Forecast. ISBN 978-0-470-94341-0

[6] Lowrie, W. (2007). Fundamentals of geophysics. Cambridge: CUP, 2nd ed.

[7] Kelvin, W. T. (1863). On the secular cooling of the earth. Transactions of the Royal Society of Edinburgh, 23, 157–170.

[8] Taylor, S. R. (2007). The Formation of the Earth and Moon. Developments in Precambrian Geology, 15, 21–30.

[9] England, P., Molnar, P., Richter, F. (2007). John Perry’s neglected critique of Kelvin’s age for the Earth: A missed opportunity in geodynamics.

[10] Dye, S. T. (2012). Geoneutrinos and the radioactive power of the Earth.Reviews of Geophysics, 50(3).

[11] Gando, A., Dwyer, D., McKeown, R., & Zhang, C. (2011). Partial radiogenic heat model for Earth revealed by geoneutrino measurements. Nature Geoscience, 4(9).

[12] Francis.A, (2007). Erta Ale, Ethiopia. Volcano World. Oregon State University.

[13] Donald G., Ink H., (2007). Standard book for Electrical Engineers, McGraw Hill.

[14] Oppen H., and Gezehagn Y., (2012). Thermal imaging of an active lava lake: Erta Ale volcano,

[15] Francis P., Oppenheimer C., and Stevenson, D., (1993). Endogenous growth of persistently active volcanos. Nature, 366, 554-557.

[16] Wilfred A., (2014). Iceland Deep Drilling Project: The first well, IDDP-1, drilled into magma

[17] Wilfred A., (2014). Iceland Deep Drilling Project Finds Magma

[18] Trausti H., Sigurdur M., Kristján E., Sigrún Nanna K., 2014, Pilot testing of handling the fluids from the IDDP-1 exploratory geothermal well, Krafla, N.E. Iceland

[19] Yunus A. Cengel, Michael A. Boles, (2006), thermodynamics an engineering approach.

[20] Steve Connor, (2014). Boiler Basics Design & Application Differences

[21] Fernandes R., Ambrosius B., Noomen R., Bastos L., (2004). "Angular velocities of Nubia and Somalia from continuous GPS data: implications on present-day relative kinematics".

[22] Lorraine F., Talfan B., Jon B., Richard A., & Elias L., (2012). Integrated field, satellite and petrological observations of the November 2010 eruption of Erta Ale.

[23] Esper S., (1929). The temperatures of magmas. Larsen, Harvard University.

[24] Berhanu G., (2008). Geothermal exploration and development in Ethiopia.

[25] Elizabeth H., (2016). Earth's Core 1,000 Degrees Hotter Than Expected.

[26] Samson T., (2016). Highlights of the Ethiopian energy sector.

[27] Frank p., Incropera A., David D., (2007). Fundamentals of Heat and Mass Transfer, College of Engineering University of and School of Mechanical Engineering Purdue University

[28] Worster M., Huppert, H., and Sparks R., (1993). The crystallization of lava lakes Journal of Geophysical Research, 98, 15891–15901.

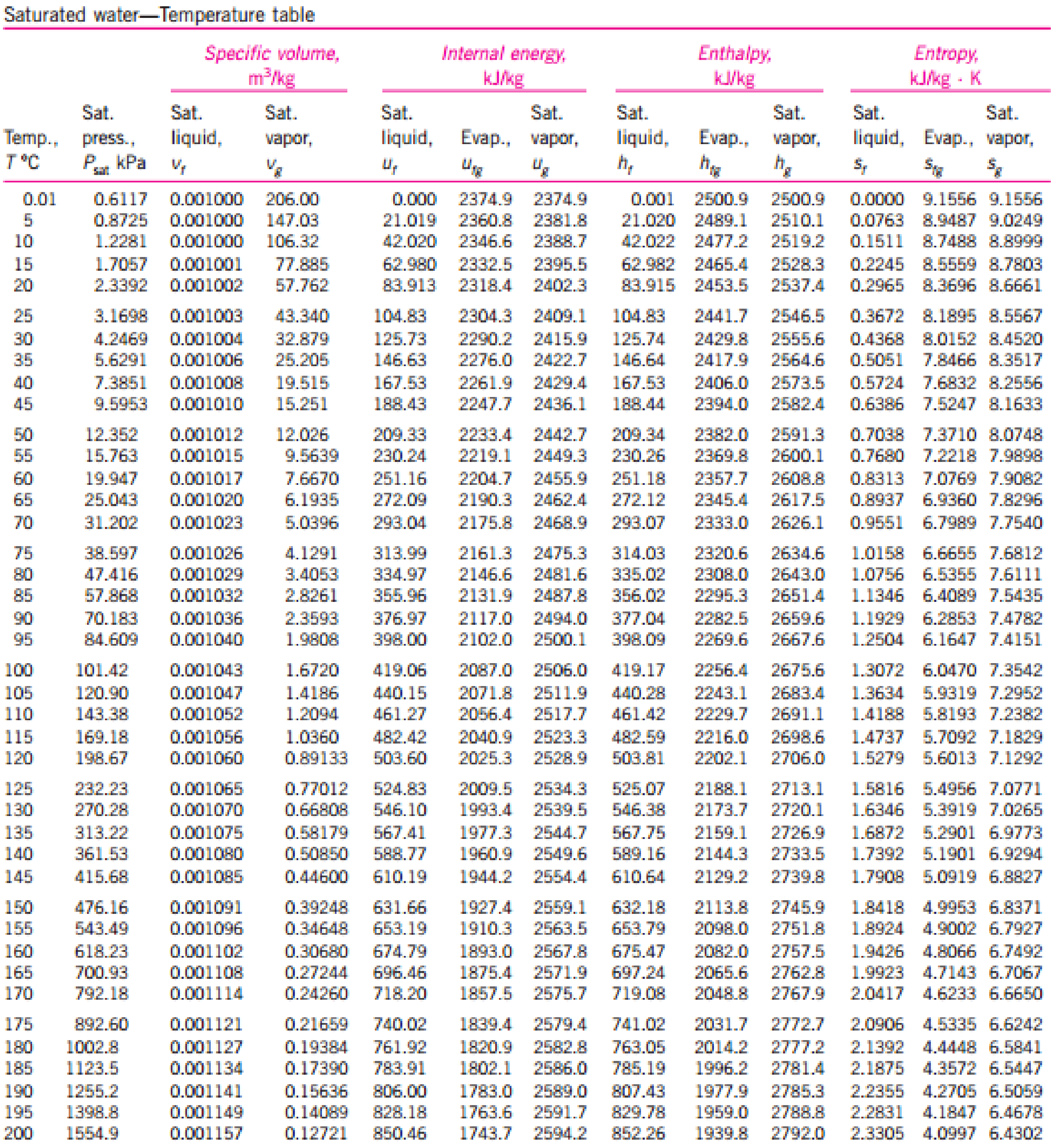
[29] Maury K., (2007). How turbine power plants work, America Bloomsbury Publishing.

[30] Glazner A., Bartley J., Coleman D., Gray W., Taylor Z., (2004). Are plutons assembled over millions of years by amalgamation from small magma chambers? GSA Today.

[31] Leuthold J., (2012). Time resolved construction of a bimodal laccolith, Torres Del Paine, Patagonia, Earth and Planetary Science Letters.

[32] Eugene C, (1998). Thermal properties of Rocks, United States department of Geological Survey

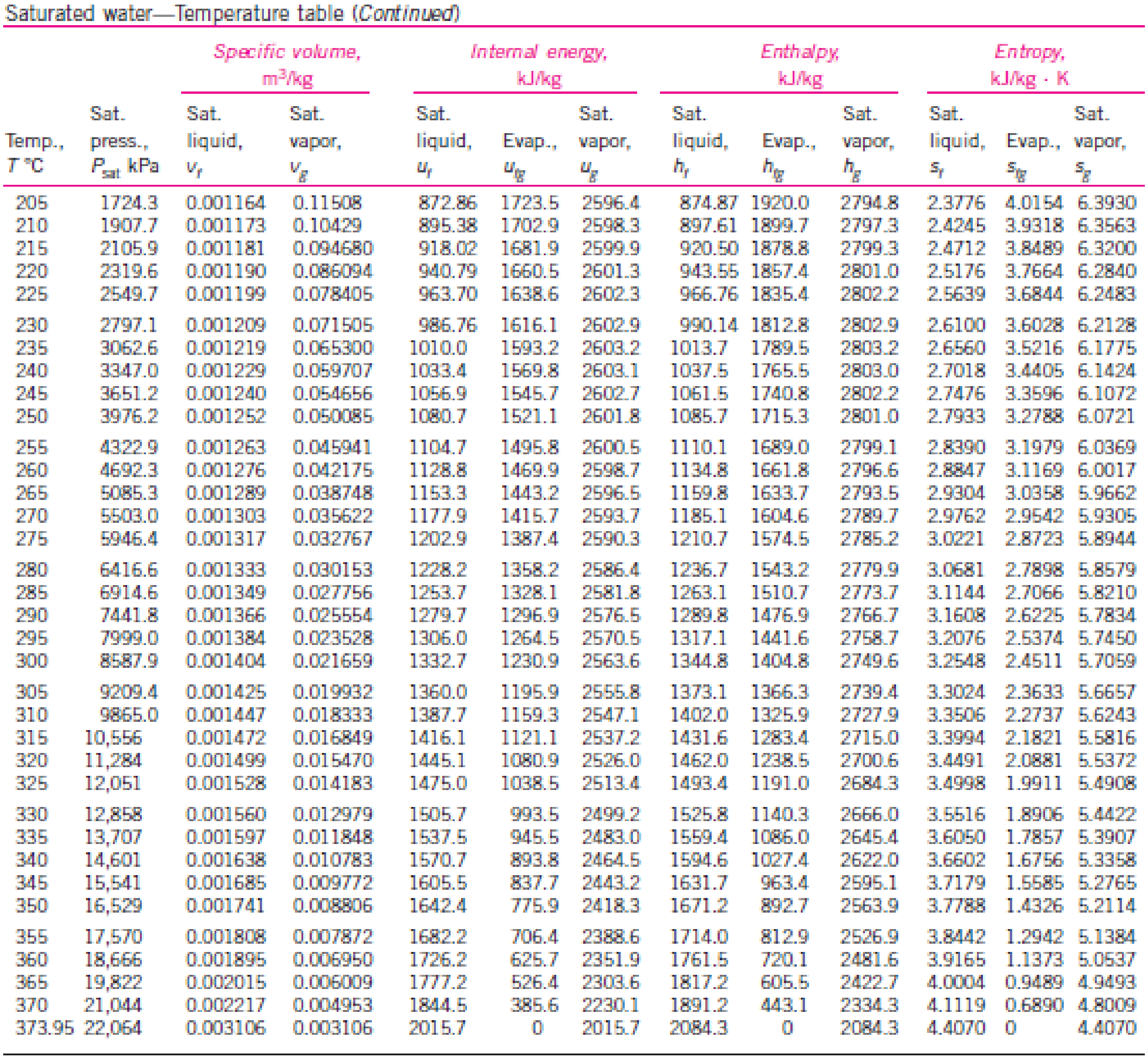
# Appendix A



Saturated water—Temperature table

| | | Specific volume, $m^3/kg$ | | Internal energy, kJ/kg | | | Enthalpy, kJ/kg | | | Entropy, kJ/kg · K | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temp., $T$ °C | Sat. press., $P_{sat}$ kPa | Sat. liquid, $v_f$ | Sat. vapor, $v_g$ | Sat. liquid, $u_f$ | Evap., $u_{fg}$ | Sat. vapor, $u_g$ | Sat. liquid, $h_f$ | Evap., $h_{fg}$ | Sat. vapor, $h_g$ | Sat. liquid, $s_f$ | Evap., $s_{fg}$ | Sat. vapor, $s_g$ |
| 0.01 | 0.6117 | 0.001000 | 206.00 | 0.000 | 2374.9 | 2374.9 | 0.001 | 2500.9 | 2500.9 | 0.0000 | 9.1556 | 9.1556 |
| 5 | 0.8725 | 0.001000 | 147.03 | 21.019 | 2360.8 | 2381.8 | 21.020 | 2489.1 | 2510.1 | 0.0763 | 8.9487 | 9.0249 |
| 10 | 1.2281 | 0.001000 | 106.32 | 42.020 | 2346.6 | 2388.7 | 42.022 | 2477.2 | 2519.2 | 0.1511 | 8.7488 | 8.8999 |
| 15 | 1.7057 | 0.001001 | 77.885 | 62.980 | 2332.5 | 2395.5 | 62.982 | 2465.4 | 2528.3 | 0.2245 | 8.5559 | 8.7803 |
| 20 | 2.3392 | 0.001002 | 57.762 | 83.913 | 2318.4 | 2402.3 | 83.915 | 2453.5 | 2537.4 | 0.2965 | 8.3696 | 8.6661 |
| 25 | 3.1698 | 0.001003 | 43.340 | 104.83 | 2304.3 | 2409.1 | 104.83 | 2441.7 | 2546.5 | 0.3672 | 8.1895 | 8.5567 |
| 30 | 4.2469 | 0.001004 | 32.879 | 125.73 | 2290.2 | 2415.9 | 125.74 | 2429.8 | 2555.6 | 0.4368 | 8.0152 | 8.4520 |
| 35 | 5.6291 | 0.001006 | 25.205 | 146.63 | 2276.0 | 2422.7 | 146.64 | 2417.9 | 2564.6 | 0.5051 | 7.8466 | 8.3517 |
| 40 | 7.3851 | 0.001008 | 19.515 | 167.53 | 2261.9 | 2429.4 | 167.53 | 2406.0 | 2573.5 | 0.5724 | 7.6832 | 8.2556 |
| 45 | 9.5953 | 0.001010 | 15.251 | 188.43 | 2247.7 | 2436.1 | 188.44 | 2394.0 | 2582.4 | 0.6386 | 7.5247 | 8.1633 |
| 50 | 12.352 | 0.001012 | 12.026 | 209.33 | 2233.4 | 2442.7 | 209.34 | 2382.0 | 2591.3 | 0.7038 | 7.3710 | 8.0748 |
| 55 | 15.763 | 0.001015 | 9.5639 | 230.24 | 2219.1 | 2449.3 | 230.26 | 2369.8 | 2600.1 | 0.7680 | 7.2218 | 7.9898 |
| 60 | 19.947 | 0.001017 | 7.6670 | 251.16 | 2204.7 | 2455.9 | 251.18 | 2357.7 | 2608.8 | 0.8313 | 7.0769 | 7.9082 |
| 65 | 25.043 | 0.001020 | 6.1935 | 272.09 | 2190.3 | 2462.4 | 272.12 | 2345.4 | 2617.5 | 0.8937 | 6.9360 | 7.8296 |
| 70 | 31.202 | 0.001023 | 5.0396 | 293.04 | 2175.8 | 2468.9 | 293.07 | 2333.0 | 2626.1 | 0.9551 | 6.7989 | 7.7540 |
| 75 | 38.597 | 0.001026 | 4.1291 | 313.99 | 2161.3 | 2475.3 | 314.03 | 2320.6 | 2634.6 | 1.0158 | 6.6655 | 7.6812 |
| 80 | 47.416 | 0.001029 | 3.4053 | 334.97 | 2146.6 | 2481.6 | 335.02 | 2308.0 | 2643.0 | 1.0756 | 6.5355 | 7.6111 |
| 85 | 57.868 | 0.001032 | 2.8261 | 355.96 | 2131.9 | 2487.8 | 356.02 | 2295.3 | 2651.4 | 1.1346 | 6.4089 | 7.5435 |
| 90 | 70.183 | 0.001036 | 2.3593 | 376.97 | 2117.0 | 2494.0 | 377.04 | 2282.5 | 2659.6 | 1.1929 | 6.2853 | 7.4782 |
| 95 | 84.609 | 0.001040 | 1.9808 | 398.00 | 2102.0 | 2500.1 | 398.09 | 2269.6 | 2667.6 | 1.2504 | 6.1647 | 7.4151 |
| 100 | 101.42 | 0.001043 | 1.6720 | 419.06 | 2087.0 | 2506.0 | 419.17 | 2256.4 | 2675.6 | 1.3072 | 6.0470 | 7.3542 |
| 105 | 120.90 | 0.001047 | 1.4186 | 440.15 | 2071.8 | 2511.9 | 440.28 | 2243.1 | 2683.4 | 1.3634 | 5.9319 | 7.2952 |
| 110 | 143.38 | 0.001052 | 1.2094 | 461.27 | 2056.4 | 2517.7 | 461.42 | 2229.7 | 2691.1 | 1.4188 | 5.8193 | 7.2382 |
| 115 | 169.18 | 0.001056 | 1.0360 | 482.42 | 2040.9 | 2523.3 | 482.59 | 2216.0 | 2698.6 | 1.4737 | 5.7092 | 7.1829 |
| 120 | 198.67 | 0.001060 | 0.89133 | 503.60 | 2025.3 | 2528.9 | 503.81 | 2202.1 | 2706.0 | 1.5279 | 5.6013 | 7.1292 |
| 125 | 232.23 | 0.001065 | 0.77012 | 524.83 | 2009.5 | 2534.3 | 525.07 | 2188.1 | 2713.1 | 1.5816 | 5.4956 | 7.0771 |
| 130 | 270.28 | 0.001070 | 0.66808 | 546.10 | 1993.4 | 2539.5 | 546.38 | 2173.7 | 2720.1 | 1.6346 | 5.3919 | 7.0265 |
| 135 | 313.22 | 0.001075 | 0.58179 | 567.41 | 1977.3 | 2544.7 | 567.75 | 2159.1 | 2726.9 | 1.6872 | 5.2901 | 6.9773 |
| 140 | 361.53 | 0.001080 | 0.50850 | 588.77 | 1960.9 | 2549.6 | 589.16 | 2144.3 | 2733.5 | 1.7392 | 5.1901 | 6.9294 |
| 145 | 415.68 | 0.001085 | 0.44600 | 610.19 | 1944.2 | 2554.4 | 610.64 | 2129.2 | 2739.8 | 1.7908 | 5.0919 | 6.8827 |
| 150 | 476.16 | 0.001091 | 0.39248 | 631.66 | 1927.4 | 2559.1 | 632.18 | 2113.8 | 2745.9 | 1.8418 | 4.9953 | 6.8371 |
| 155 | 543.49 | 0.001096 | 0.34648 | 653.19 | 1910.3 | 2563.5 | 653.79 | 2098.0 | 2751.8 | 1.8924 | 4.9002 | 6.7927 |
| 160 | 618.23 | 0.001102 | 0.30680 | 674.79 | 1893.0 | 2567.8 | 675.47 | 2082.0 | 2757.5 | 1.9426 | 4.8066 | 6.7492 |
| 165 | 700.93 | 0.001108 | 0.27244 | 696.46 | 1875.4 | 2571.9 | 697.24 | 2065.6 | 2762.8 | 1.9923 | 4.7143 | 6.7067 |
| 170 | 792.18 | 0.001114 | 0.24260 | 718.20 | 1857.5 | 2575.7 | 719.08 | 2048.8 | 2767.9 | 2.0417 | 4.6233 | 6.6650 |
| 175 | 892.60 | 0.001121 | 0.21659 | 740.02 | 1839.4 | 2579.4 | 741.02 | 2031.7 | 2772.7 | 2.0906 | 4.5335 | 6.6242 |
| 180 | 1002.8 | 0.001127 | 0.19384 | 761.92 | 1820.9 | 2582.8 | 763.05 | 2014.2 | 2777.2 | 2.1392 | 4.4448 | 6.5841 |
| 185 | 1123.5 | 0.001134 | 0.17390 | 783.91 | 1802.1 | 2586.0 | 785.19 | 1996.2 | 2781.4 | 2.1875 | 4.3572 | 6.5447 |
| 190 | 1255.2 | 0.001141 | 0.15636 | 806.00 | 1783.0 | 2589.0 | 807.43 | 1977.9 | 2785.3 | 2.2355 | 4.2705 | 6.5059 |
| 195 | 1398.8 | 0.001149 | 0.14089 | 828.18 | 1763.6 | 2591.7 | 829.78 | 1959.0 | 2788.8 | 2.2831 | 4.1847 | 6.4678 |
| 200 | 1554.9 | 0.001157 | 0.12721 | 850.46 | 1743.7 | 2594.2 | 852.26 | 1939.8 | 2792.0 | 2.3305 | 4.0997 | 6.4302 |

**Table 1. Saturated water – Temperature table**

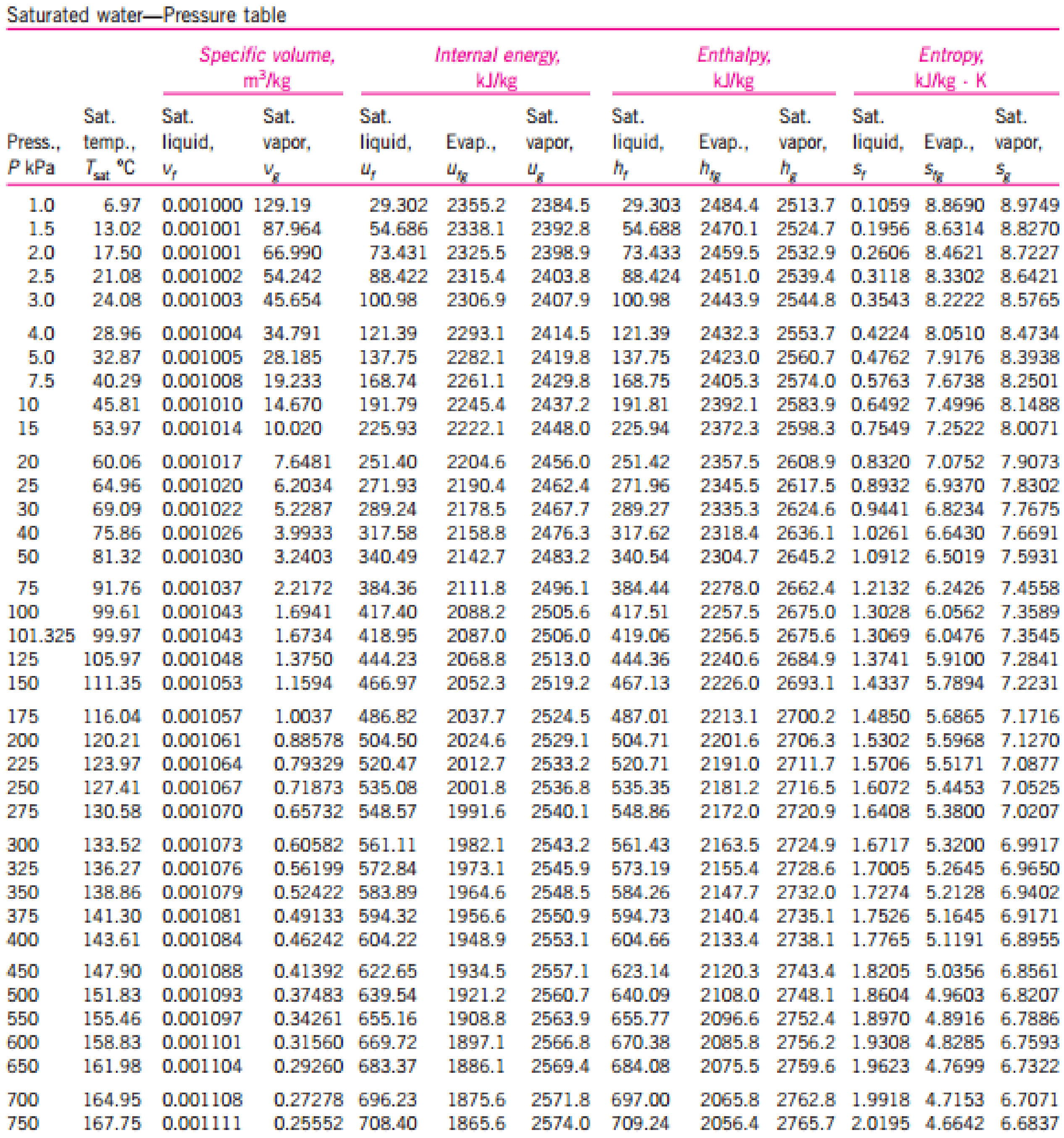


Saturated water—Temperature table (*Continued*)

| | | *Specific volume,* m³/kg | | *Internal energy,* kJ/kg | | | *Enthalpy,* kJ/kg | | | *Entropy,* kJ/kg · K | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temp., $T$ °C | Sat. press., $P_{sat}$ kPa | Sat. liquid, $v_f$ | Sat. vapor, $v_g$ | Sat. liquid, $u_f$ | Evap., $u_{fg}$ | Sat. vapor, $u_g$ | Sat. liquid, $h_f$ | Evap., $h_{fg}$ | Sat. vapor, $h_g$ | Sat. liquid, $s_f$ | Evap., $s_{fg}$ | Sat. vapor, $s_g$ |
| 205 | 1724.3 | 0.001164 | 0.11508 | 872.86 | 1723.5 | 2596.4 | 874.87 | 1920.0 | 2794.8 | 2.3776 | 4.0154 | 6.3930 |
| 210 | 1907.7 | 0.001173 | 0.10429 | 895.38 | 1702.9 | 2598.3 | 897.61 | 1899.7 | 2797.3 | 2.4245 | 3.9318 | 6.3563 |
| 215 | 2105.9 | 0.001181 | 0.094680 | 918.02 | 1681.9 | 2599.9 | 920.50 | 1878.8 | 2799.3 | 2.4712 | 3.8489 | 6.3200 |
| 220 | 2319.6 | 0.001190 | 0.086094 | 940.79 | 1660.5 | 2601.3 | 943.55 | 1857.4 | 2801.0 | 2.5176 | 3.7664 | 6.2840 |
| 225 | 2549.7 | 0.001199 | 0.078405 | 963.70 | 1638.6 | 2602.3 | 966.76 | 1835.4 | 2802.2 | 2.5639 | 3.6844 | 6.2483 |
| 230 | 2797.1 | 0.001209 | 0.071505 | 986.76 | 1616.1 | 2602.9 | 990.14 | 1812.8 | 2802.9 | 2.6100 | 3.6028 | 6.2128 |
| 235 | 3062.6 | 0.001219 | 0.065300 | 1010.0 | 1593.2 | 2603.2 | 1013.7 | 1789.5 | 2803.2 | 2.6560 | 3.5216 | 6.1775 |
| 240 | 3347.0 | 0.001229 | 0.059707 | 1033.4 | 1569.8 | 2603.1 | 1037.5 | 1765.5 | 2803.0 | 2.7018 | 3.4405 | 6.1424 |
| 245 | 3651.2 | 0.001240 | 0.054656 | 1056.9 | 1545.7 | 2602.7 | 1061.5 | 1740.8 | 2802.2 | 2.7476 | 3.3596 | 6.1072 |
| 250 | 3976.2 | 0.001252 | 0.050085 | 1080.7 | 1521.1 | 2601.8 | 1085.7 | 1715.3 | 2801.0 | 2.7933 | 3.2788 | 6.0721 |
| 255 | 4322.9 | 0.001263 | 0.045941 | 1104.7 | 1495.8 | 2600.5 | 1110.1 | 1689.0 | 2799.1 | 2.8390 | 3.1979 | 6.0369 |
| 260 | 4692.3 | 0.001276 | 0.042175 | 1128.8 | 1469.9 | 2598.7 | 1134.8 | 1661.8 | 2796.6 | 2.8847 | 3.1169 | 6.0017 |
| 265 | 5085.3 | 0.001289 | 0.038748 | 1153.3 | 1443.2 | 2596.5 | 1159.8 | 1633.7 | 2793.5 | 2.9304 | 3.0358 | 5.9662 |
| 270 | 5503.0 | 0.001303 | 0.035622 | 1177.9 | 1415.7 | 2593.7 | 1185.1 | 1604.6 | 2789.7 | 2.9762 | 2.9542 | 5.9305 |
| 275 | 5946.4 | 0.001317 | 0.032767 | 1202.9 | 1387.4 | 2590.3 | 1210.7 | 1574.5 | 2785.2 | 3.0221 | 2.8723 | 5.8944 |
| 280 | 6416.6 | 0.001333 | 0.030153 | 1228.2 | 1358.2 | 2586.4 | 1236.7 | 1543.2 | 2779.9 | 3.0681 | 2.7898 | 5.8579 |
| 285 | 6914.6 | 0.001349 | 0.027756 | 1253.7 | 1328.1 | 2581.8 | 1263.1 | 1510.7 | 2773.7 | 3.1144 | 2.7066 | 5.8210 |
| 290 | 7441.8 | 0.001366 | 0.025554 | 1279.7 | 1296.9 | 2576.5 | 1289.8 | 1476.9 | 2766.7 | 3.1608 | 2.6225 | 5.7834 |
| 295 | 7999.0 | 0.001384 | 0.023528 | 1306.0 | 1264.5 | 2570.5 | 1317.1 | 1441.6 | 2758.7 | 3.2076 | 2.5374 | 5.7450 |
| 300 | 8587.9 | 0.001404 | 0.021659 | 1332.7 | 1230.9 | 2563.6 | 1344.8 | 1404.8 | 2749.6 | 3.2548 | 2.4511 | 5.7059 |
| 305 | 9209.4 | 0.001425 | 0.019932 | 1360.0 | 1195.9 | 2555.8 | 1373.1 | 1366.3 | 2739.4 | 3.3024 | 2.3633 | 5.6657 |
| 310 | 9865.0 | 0.001447 | 0.018333 | 1387.7 | 1159.3 | 2547.1 | 1402.0 | 1325.9 | 2727.9 | 3.3506 | 2.2737 | 5.6243 |
| 315 | 10,556 | 0.001472 | 0.016849 | 1416.1 | 1121.1 | 2537.2 | 1431.6 | 1283.4 | 2715.0 | 3.3994 | 2.1821 | 5.5816 |
| 320 | 11,284 | 0.001499 | 0.015470 | 1445.1 | 1080.9 | 2526.0 | 1462.0 | 1238.5 | 2700.6 | 3.4491 | 2.0881 | 5.5372 |
| 325 | 12,051 | 0.001528 | 0.014183 | 1475.0 | 1038.5 | 2513.4 | 1493.4 | 1191.0 | 2684.3 | 3.4998 | 1.9911 | 5.4908 |
| 330 | 12,858 | 0.001560 | 0.012979 | 1505.7 | 993.5 | 2499.2 | 1525.8 | 1140.3 | 2666.0 | 3.5516 | 1.8906 | 5.4422 |
| 335 | 13,707 | 0.001597 | 0.011848 | 1537.5 | 945.5 | 2483.0 | 1559.4 | 1086.0 | 2645.4 | 3.6050 | 1.7857 | 5.3907 |
| 340 | 14,601 | 0.001638 | 0.010783 | 1570.7 | 893.8 | 2464.5 | 1594.6 | 1027.4 | 2622.0 | 3.6602 | 1.6756 | 5.3358 |
| 345 | 15,541 | 0.001685 | 0.009772 | 1605.5 | 837.7 | 2443.2 | 1631.7 | 963.4 | 2595.1 | 3.7179 | 1.5585 | 5.2765 |
| 350 | 16,529 | 0.001741 | 0.008806 | 1642.4 | 775.9 | 2418.3 | 1671.2 | 892.7 | 2563.9 | 3.7788 | 1.4326 | 5.2114 |
| 355 | 17,570 | 0.001808 | 0.007872 | 1682.2 | 706.4 | 2388.6 | 1714.0 | 812.9 | 2526.9 | 3.8442 | 1.2942 | 5.1384 |
| 360 | 18,666 | 0.001895 | 0.006950 | 1726.2 | 625.7 | 2351.9 | 1761.5 | 720.1 | 2481.6 | 3.9165 | 1.1373 | 5.0537 |
| 365 | 19,822 | 0.002015 | 0.006009 | 1777.2 | 526.4 | 2303.6 | 1817.2 | 605.5 | 2422.7 | 4.0004 | 0.9489 | 4.9493 |
| 370 | 21,044 | 0.002217 | 0.004953 | 1844.5 | 385.6 | 2230.1 | 1891.2 | 443.1 | 2334.3 | 4.1119 | 0.6890 | 4.8009 |
| 373.95 | 22,064 | 0.003106 | 0.003106 | 2015.7 | 0 | 2015.7 | 2084.3 | 0 | 2084.3 | 4.4070 | 0 | 4.4070 |

**Table 2. Saturated water – Temperature table (continued)**

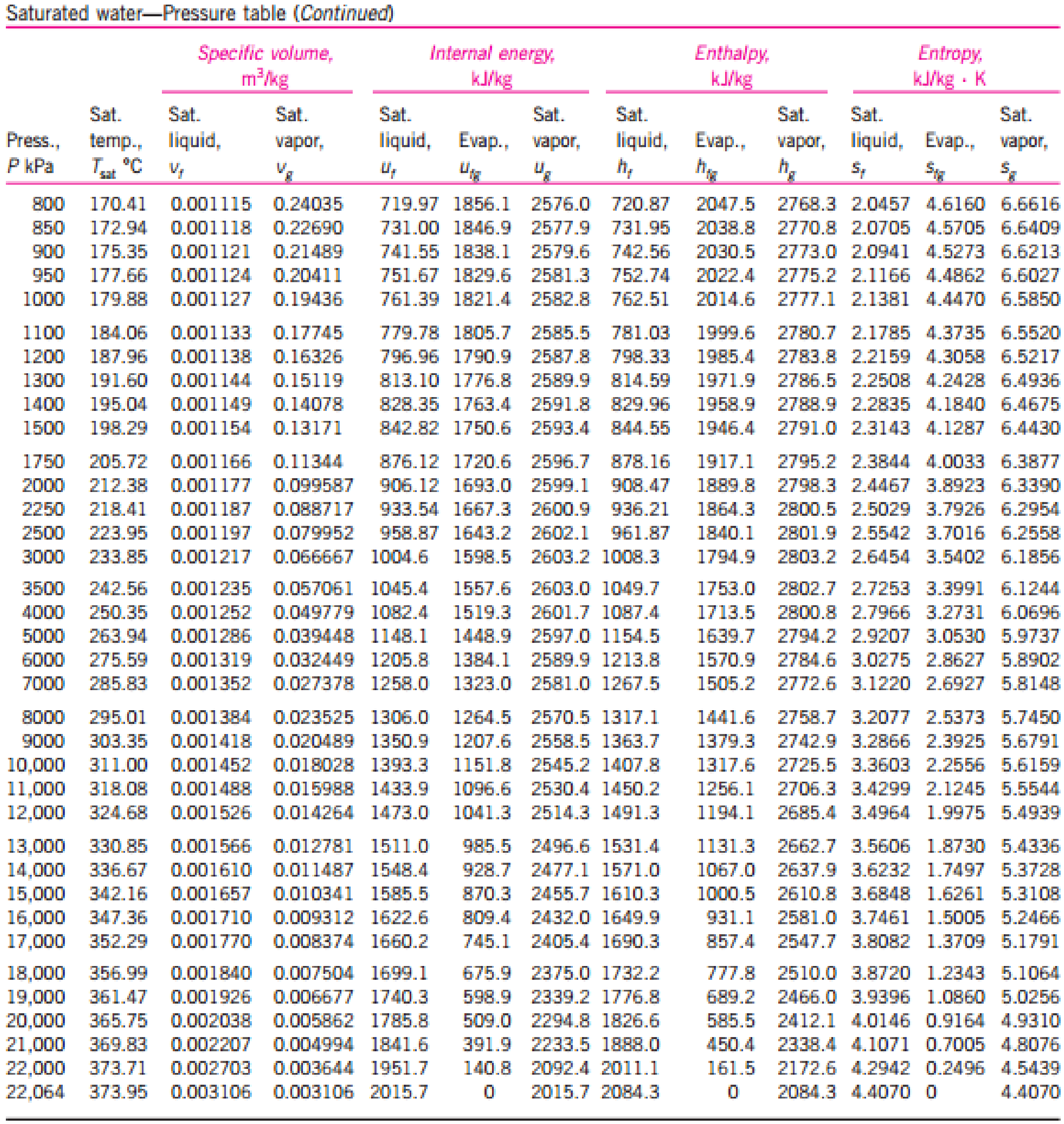
# Appendix B



Saturated water—Pressure table

| | | Specific volume, m³/kg | | Internal energy, kJ/kg | | | Enthalpy, kJ/kg | | | Entropy, kJ/kg · K | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Press., P kPa | Sat. temp., $T_{sat}$ °C | Sat. liquid, $v_f$ | Sat. vapor, $v_g$ | Sat. liquid, $u_f$ | Evap., $u_{fg}$ | Sat. vapor, $u_g$ | Sat. liquid, $h_f$ | Evap., $h_{fg}$ | Sat. vapor, $h_g$ | Sat. liquid, $s_f$ | Evap., $s_{fg}$ | Sat. vapor, $s_g$ |
| 1.0 | 6.97 | 0.001000 | 129.19 | 29.302 | 2355.2 | 2384.5 | 29.303 | 2484.4 | 2513.7 | 0.1059 | 8.8690 | 8.9749 |
| 1.5 | 13.02 | 0.001001 | 87.964 | 54.686 | 2338.1 | 2392.8 | 54.688 | 2470.1 | 2524.7 | 0.1956 | 8.6314 | 8.8270 |
| 2.0 | 17.50 | 0.001001 | 66.990 | 73.431 | 2325.5 | 2398.9 | 73.433 | 2459.5 | 2532.9 | 0.2606 | 8.4621 | 8.7227 |
| 2.5 | 21.08 | 0.001002 | 54.242 | 88.422 | 2315.4 | 2403.8 | 88.424 | 2451.0 | 2539.4 | 0.3118 | 8.3302 | 8.6421 |
| 3.0 | 24.08 | 0.001003 | 45.654 | 100.98 | 2306.9 | 2407.9 | 100.98 | 2443.9 | 2544.8 | 0.3543 | 8.2222 | 8.5765 |
| 4.0 | 28.96 | 0.001004 | 34.791 | 121.39 | 2293.1 | 2414.5 | 121.39 | 2432.3 | 2553.7 | 0.4224 | 8.0510 | 8.4734 |
| 5.0 | 32.87 | 0.001005 | 28.185 | 137.75 | 2282.1 | 2419.8 | 137.75 | 2423.0 | 2560.7 | 0.4762 | 7.9176 | 8.3938 |
| 7.5 | 40.29 | 0.001008 | 19.233 | 168.74 | 2261.1 | 2429.8 | 168.75 | 2405.3 | 2574.0 | 0.5763 | 7.6738 | 8.2501 |
| 10 | 45.81 | 0.001010 | 14.670 | 191.79 | 2245.4 | 2437.2 | 191.81 | 2392.1 | 2583.9 | 0.6492 | 7.4996 | 8.1488 |
| 15 | 53.97 | 0.001014 | 10.020 | 225.93 | 2222.1 | 2448.0 | 225.94 | 2372.3 | 2598.3 | 0.7549 | 7.2522 | 8.0071 |
| 20 | 60.06 | 0.001017 | 7.6481 | 251.40 | 2204.6 | 2456.0 | 251.42 | 2357.5 | 2608.9 | 0.8320 | 7.0752 | 7.9073 |
| 25 | 64.96 | 0.001020 | 6.2034 | 271.93 | 2190.4 | 2462.4 | 271.96 | 2345.5 | 2617.5 | 0.8932 | 6.9370 | 7.8302 |
| 30 | 69.09 | 0.001022 | 5.2287 | 289.24 | 2178.5 | 2467.7 | 289.27 | 2335.3 | 2624.6 | 0.9441 | 6.8234 | 7.7675 |
| 40 | 75.86 | 0.001026 | 3.9933 | 317.58 | 2158.8 | 2476.3 | 317.62 | 2318.4 | 2636.1 | 1.0261 | 6.6430 | 7.6691 |
| 50 | 81.32 | 0.001030 | 3.2403 | 340.49 | 2142.7 | 2483.2 | 340.54 | 2304.7 | 2645.2 | 1.0912 | 6.5019 | 7.5931 |
| 75 | 91.76 | 0.001037 | 2.2172 | 384.36 | 2111.8 | 2496.1 | 384.44 | 2278.0 | 2662.4 | 1.2132 | 6.2426 | 7.4558 |
| 100 | 99.61 | 0.001043 | 1.6941 | 417.40 | 2088.2 | 2505.6 | 417.51 | 2257.5 | 2675.0 | 1.3028 | 6.0562 | 7.3589 |
| 101.325 | 99.97 | 0.001043 | 1.6734 | 418.95 | 2087.0 | 2506.0 | 419.06 | 2256.5 | 2675.6 | 1.3069 | 6.0476 | 7.3545 |
| 125 | 105.97 | 0.001048 | 1.3750 | 444.23 | 2068.8 | 2513.0 | 444.36 | 2240.6 | 2684.9 | 1.3741 | 5.9100 | 7.2841 |
| 150 | 111.35 | 0.001053 | 1.1594 | 466.97 | 2052.3 | 2519.2 | 467.13 | 2226.0 | 2693.1 | 1.4337 | 5.7894 | 7.2231 |
| 175 | 116.04 | 0.001057 | 1.0037 | 486.82 | 2037.7 | 2524.5 | 487.01 | 2213.1 | 2700.2 | 1.4850 | 5.6865 | 7.1716 |
| 200 | 120.21 | 0.001061 | 0.88578 | 504.50 | 2024.6 | 2529.1 | 504.71 | 2201.6 | 2706.3 | 1.5302 | 5.5968 | 7.1270 |
| 225 | 123.97 | 0.001064 | 0.79329 | 520.47 | 2012.7 | 2533.2 | 520.71 | 2191.0 | 2711.7 | 1.5706 | 5.5171 | 7.0877 |
| 250 | 127.41 | 0.001067 | 0.71873 | 535.08 | 2001.8 | 2536.8 | 535.35 | 2181.2 | 2716.5 | 1.6072 | 5.4453 | 7.0525 |
| 275 | 130.58 | 0.001070 | 0.65732 | 548.57 | 1991.6 | 2540.1 | 548.86 | 2172.0 | 2720.9 | 1.6408 | 5.3800 | 7.0207 |
| 300 | 133.52 | 0.001073 | 0.60582 | 561.11 | 1982.1 | 2543.2 | 561.43 | 2163.5 | 2724.9 | 1.6717 | 5.3200 | 6.9917 |
| 325 | 136.27 | 0.001076 | 0.56199 | 572.84 | 1973.1 | 2545.9 | 573.19 | 2155.4 | 2728.6 | 1.7005 | 5.2645 | 6.9650 |
| 350 | 138.86 | 0.001079 | 0.52422 | 583.89 | 1964.6 | 2548.5 | 584.26 | 2147.7 | 2732.0 | 1.7274 | 5.2128 | 6.9402 |
| 375 | 141.30 | 0.001081 | 0.49133 | 594.32 | 1956.6 | 2550.9 | 594.73 | 2140.4 | 2735.1 | 1.7526 | 5.1645 | 6.9171 |
| 400 | 143.61 | 0.001084 | 0.46242 | 604.22 | 1948.9 | 2553.1 | 604.66 | 2133.4 | 2738.1 | 1.7765 | 5.1191 | 6.8955 |
| 450 | 147.90 | 0.001088 | 0.41392 | 622.65 | 1934.5 | 2557.1 | 623.14 | 2120.3 | 2743.4 | 1.8205 | 5.0356 | 6.8561 |
| 500 | 151.83 | 0.001093 | 0.37483 | 639.54 | 1921.2 | 2560.7 | 640.09 | 2108.0 | 2748.1 | 1.8604 | 4.9603 | 6.8207 |
| 550 | 155.46 | 0.001097 | 0.34261 | 655.16 | 1908.8 | 2563.9 | 655.77 | 2096.6 | 2752.4 | 1.8970 | 4.8916 | 6.7886 |
| 600 | 158.83 | 0.001101 | 0.31560 | 669.72 | 1897.1 | 2566.8 | 670.38 | 2085.8 | 2756.2 | 1.9308 | 4.8285 | 6.7593 |
| 650 | 161.98 | 0.001104 | 0.29260 | 683.37 | 1886.1 | 2569.4 | 684.08 | 2075.5 | 2759.6 | 1.9623 | 4.7699 | 6.7322 |
| 700 | 164.95 | 0.001108 | 0.27278 | 696.23 | 1875.6 | 2571.8 | 697.00 | 2065.8 | 2762.8 | 1.9918 | 4.7153 | 6.7071 |
| 750 | 167.75 | 0.001111 | 0.25552 | 708.40 | 1865.6 | 2574.0 | 709.24 | 2056.4 | 2765.7 | 2.0195 | 4.6642 | 6.6837 |

**Table 3. Saturated water – Pressure table**

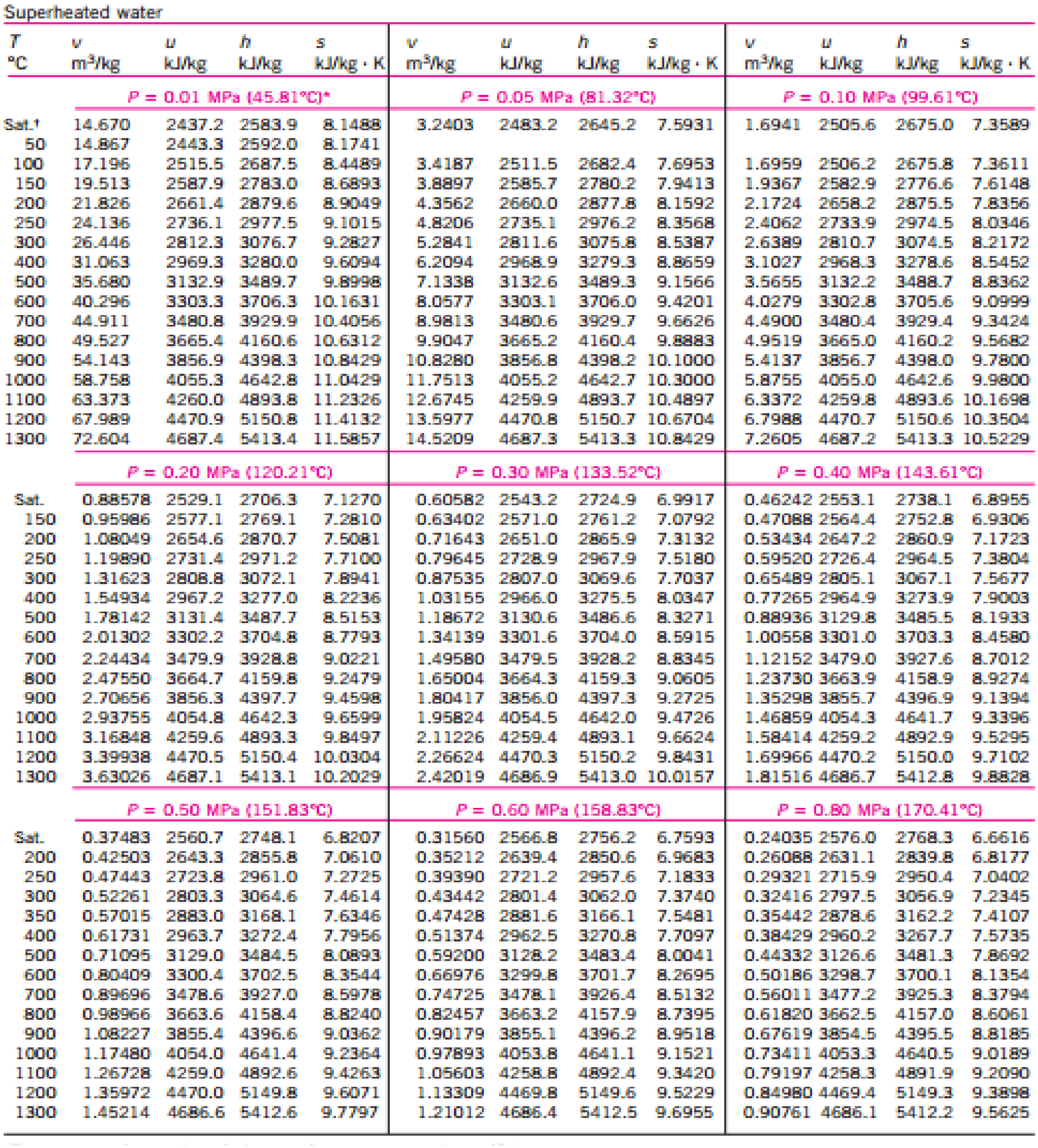


Saturated water—Pressure table (*Continued*)

| | | Specific volume, $m^3/kg$ | | Internal energy, kJ/kg | | | Enthalpy, kJ/kg | | | Entropy, kJ/kg · K | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Press., $P$ kPa | Sat. temp., $T_{sat}$ °C | Sat. liquid, $v_f$ | Sat. vapor, $v_g$ | Sat. liquid, $u_f$ | Evap., $u_{fg}$ | Sat. vapor, $u_g$ | Sat. liquid, $h_f$ | Evap., $h_{fg}$ | Sat. vapor, $h_g$ | Sat. liquid, $s_f$ | Evap., $s_{fg}$ | Sat. vapor, $s_g$ |
| 800 | 170.41 | 0.001115 | 0.24035 | 719.97 | 1856.1 | 2576.0 | 720.87 | 2047.5 | 2768.3 | 2.0457 | 4.6160 | 6.6616 |
| 850 | 172.94 | 0.001118 | 0.22690 | 731.00 | 1846.9 | 2577.9 | 731.95 | 2038.8 | 2770.8 | 2.0705 | 4.5705 | 6.6409 |
| 900 | 175.35 | 0.001121 | 0.21489 | 741.55 | 1838.1 | 2579.6 | 742.56 | 2030.5 | 2773.0 | 2.0941 | 4.5273 | 6.6213 |
| 950 | 177.66 | 0.001124 | 0.20411 | 751.67 | 1829.6 | 2581.3 | 752.74 | 2022.4 | 2775.2 | 2.1166 | 4.4862 | 6.6027 |
| 1000 | 179.88 | 0.001127 | 0.19436 | 761.39 | 1821.4 | 2582.8 | 762.51 | 2014.6 | 2777.1 | 2.1381 | 4.4470 | 6.5850 |
| 1100 | 184.06 | 0.001133 | 0.17745 | 779.78 | 1805.7 | 2585.5 | 781.03 | 1999.6 | 2780.7 | 2.1785 | 4.3735 | 6.5520 |
| 1200 | 187.96 | 0.001138 | 0.16326 | 796.96 | 1790.9 | 2587.8 | 798.33 | 1985.4 | 2783.8 | 2.2159 | 4.3058 | 6.5217 |
| 1300 | 191.60 | 0.001144 | 0.15119 | 813.10 | 1776.8 | 2589.9 | 814.59 | 1971.9 | 2786.5 | 2.2508 | 4.2428 | 6.4936 |
| 1400 | 195.04 | 0.001149 | 0.14078 | 828.35 | 1763.4 | 2591.8 | 829.96 | 1958.9 | 2788.9 | 2.2835 | 4.1840 | 6.4675 |
| 1500 | 198.29 | 0.001154 | 0.13171 | 842.82 | 1750.6 | 2593.4 | 844.55 | 1946.4 | 2791.0 | 2.3143 | 4.1287 | 6.4430 |
| 1750 | 205.72 | 0.001166 | 0.11344 | 876.12 | 1720.6 | 2596.7 | 878.16 | 1917.1 | 2795.2 | 2.3844 | 4.0033 | 6.3877 |
| 2000 | 212.38 | 0.001177 | 0.099587 | 906.12 | 1693.0 | 2599.1 | 908.47 | 1889.8 | 2798.3 | 2.4467 | 3.8923 | 6.3390 |
| 2250 | 218.41 | 0.001187 | 0.088717 | 933.54 | 1667.3 | 2600.9 | 936.21 | 1864.3 | 2800.5 | 2.5029 | 3.7926 | 6.2954 |
| 2500 | 223.95 | 0.001197 | 0.079952 | 958.87 | 1643.2 | 2602.1 | 961.87 | 1840.1 | 2801.9 | 2.5542 | 3.7016 | 6.2558 |
| 3000 | 233.85 | 0.001217 | 0.066667 | 1004.6 | 1598.5 | 2603.2 | 1008.3 | 1794.9 | 2803.2 | 2.6454 | 3.5402 | 6.1856 |
| 3500 | 242.56 | 0.001235 | 0.057061 | 1045.4 | 1557.6 | 2603.0 | 1049.7 | 1753.0 | 2802.7 | 2.7253 | 3.3991 | 6.1244 |
| 4000 | 250.35 | 0.001252 | 0.049779 | 1082.4 | 1519.3 | 2601.7 | 1087.4 | 1713.5 | 2800.8 | 2.7966 | 3.2731 | 6.0696 |
| 5000 | 263.94 | 0.001286 | 0.039448 | 1148.1 | 1448.9 | 2597.0 | 1154.5 | 1639.7 | 2794.2 | 2.9207 | 3.0530 | 5.9737 |
| 6000 | 275.59 | 0.001319 | 0.032449 | 1205.8 | 1384.1 | 2589.9 | 1213.8 | 1570.9 | 2784.6 | 3.0275 | 2.8627 | 5.8902 |
| 7000 | 285.83 | 0.001352 | 0.027378 | 1258.0 | 1323.0 | 2581.0 | 1267.5 | 1505.2 | 2772.6 | 3.1220 | 2.6927 | 5.8148 |
| 8000 | 295.01 | 0.001384 | 0.023525 | 1306.0 | 1264.5 | 2570.5 | 1317.1 | 1441.6 | 2758.7 | 3.2077 | 2.5373 | 5.7450 |
| 9000 | 303.35 | 0.001418 | 0.020489 | 1350.9 | 1207.6 | 2558.5 | 1363.7 | 1379.3 | 2742.9 | 3.2866 | 2.3925 | 5.6791 |
| 10,000 | 311.00 | 0.001452 | 0.018028 | 1393.3 | 1151.8 | 2545.2 | 1407.8 | 1317.6 | 2725.5 | 3.3603 | 2.2556 | 5.6159 |
| 11,000 | 318.08 | 0.001488 | 0.015988 | 1433.9 | 1096.6 | 2530.4 | 1450.2 | 1256.1 | 2706.3 | 3.4299 | 2.1245 | 5.5544 |
| 12,000 | 324.68 | 0.001526 | 0.014264 | 1473.0 | 1041.3 | 2514.3 | 1491.3 | 1194.1 | 2685.4 | 3.4964 | 1.9975 | 5.4939 |
| 13,000 | 330.85 | 0.001566 | 0.012781 | 1511.0 | 985.5 | 2496.6 | 1531.4 | 1131.3 | 2662.7 | 3.5606 | 1.8730 | 5.4336 |
| 14,000 | 336.67 | 0.001610 | 0.011487 | 1548.4 | 928.7 | 2477.1 | 1571.0 | 1067.0 | 2637.9 | 3.6232 | 1.7497 | 5.3728 |
| 15,000 | 342.16 | 0.001657 | 0.010341 | 1585.5 | 870.3 | 2455.7 | 1610.3 | 1000.5 | 2610.8 | 3.6848 | 1.6261 | 5.3108 |
| 16,000 | 347.36 | 0.001710 | 0.009312 | 1622.6 | 809.4 | 2432.0 | 1649.9 | 931.1 | 2581.0 | 3.7461 | 1.5005 | 5.2466 |
| 17,000 | 352.29 | 0.001770 | 0.008374 | 1660.2 | 745.1 | 2405.4 | 1690.3 | 857.4 | 2547.7 | 3.8082 | 1.3709 | 5.1791 |
| 18,000 | 356.99 | 0.001840 | 0.007504 | 1699.1 | 675.9 | 2375.0 | 1732.2 | 777.8 | 2510.0 | 3.8720 | 1.2343 | 5.1064 |
| 19,000 | 361.47 | 0.001926 | 0.006677 | 1740.3 | 598.9 | 2339.2 | 1776.8 | 689.2 | 2466.0 | 3.9396 | 1.0860 | 5.0256 |
| 20,000 | 365.75 | 0.002038 | 0.005862 | 1785.8 | 509.0 | 2294.8 | 1826.6 | 585.5 | 2412.1 | 4.0146 | 0.9164 | 4.9310 |
| 21,000 | 369.83 | 0.002207 | 0.004994 | 1841.6 | 391.9 | 2233.5 | 1888.0 | 450.4 | 2338.4 | 4.1071 | 0.7005 | 4.8076 |
| 22,000 | 373.71 | 0.002703 | 0.003644 | 1951.7 | 140.8 | 2092.4 | 2011.1 | 161.5 | 2172.6 | 4.2942 | 0.2496 | 4.5439 |
| 22,064 | 373.95 | 0.003106 | 0.003106 | 2015.7 | 0 | 2015.7 | 2084.3 | 0 | 2084.3 | 4.4070 | 0 | 4.4070 |

**Table 4. Saturated water – Pressure table (continued)**

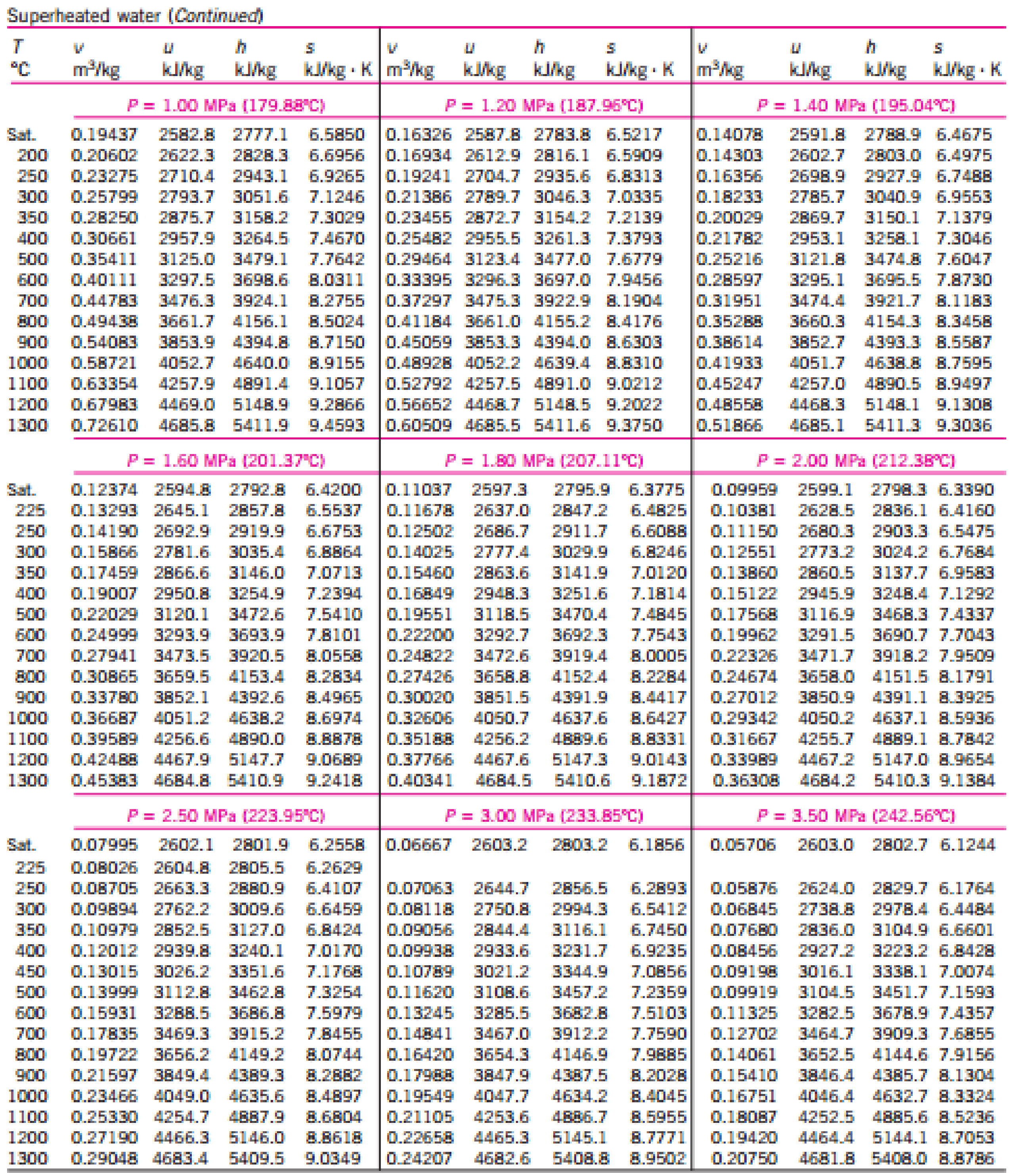
# Appendix C



Superheated water

| T °C | v m$^3$/kg | u kJ/kg | h kJ/kg | s kJ/kg · K | v m$^3$/kg | u kJ/kg | h kJ/kg | s kJ/kg · K | v m$^3$/kg | u kJ/kg | h kJ/kg | s kJ/kg · K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P = 0.01 MPa (45.81°C)* | | | | P = 0.05 MPa (81.32°C) | | | | P = 0.10 MPa (99.61°C) | | | |
| Sat.† | 14.670 | 2437.2 | 2583.9 | 8.1488 | 3.2403 | 2483.2 | 2645.2 | 7.5931 | 1.6941 | 2505.6 | 2675.0 | 7.3589 |
| 50 | 14.867 | 2443.3 | 2592.0 | 8.1741 | | | | | | | | |
| 100 | 17.196 | 2515.5 | 2687.5 | 8.4489 | 3.4187 | 2511.5 | 2682.4 | 7.6953 | 1.6959 | 2506.2 | 2675.8 | 7.3611 |
| 150 | 19.513 | 2587.9 | 2783.0 | 8.6893 | 3.8897 | 2585.7 | 2780.2 | 7.9413 | 1.9367 | 2582.9 | 2776.6 | 7.6148 |
| 200 | 21.826 | 2661.4 | 2879.6 | 8.9049 | 4.3562 | 2660.0 | 2877.8 | 8.1592 | 2.1724 | 2658.2 | 2875.5 | 7.8356 |
| 250 | 24.136 | 2736.1 | 2977.5 | 9.1015 | 4.8206 | 2735.1 | 2976.2 | 8.3568 | 2.4062 | 2733.9 | 2974.5 | 8.0346 |
| 300 | 26.446 | 2812.3 | 3076.7 | 9.2827 | 5.2841 | 2811.6 | 3075.8 | 8.5387 | 2.6389 | 2810.7 | 3074.5 | 8.2172 |
| 400 | 31.063 | 2969.3 | 3280.0 | 9.6094 | 6.2094 | 2968.9 | 3279.3 | 8.8659 | 3.1027 | 2968.3 | 3278.6 | 8.5452 |
| 500 | 35.680 | 3132.9 | 3489.7 | 9.8998 | 7.1338 | 3132.6 | 3489.3 | 9.1566 | 3.5655 | 3132.2 | 3488.7 | 8.8362 |
| 600 | 40.296 | 3303.3 | 3706.3 | 10.1631 | 8.0577 | 3303.1 | 3706.0 | 9.4201 | 4.0279 | 3302.8 | 3705.6 | 9.0999 |
| 700 | 44.911 | 3480.8 | 3929.9 | 10.4056 | 8.9813 | 3480.6 | 3929.7 | 9.6626 | 4.4900 | 3480.4 | 3929.4 | 9.3424 |
| 800 | 49.527 | 3665.4 | 4160.6 | 10.6312 | 9.9047 | 3665.2 | 4160.4 | 9.8883 | 4.9519 | 3665.0 | 4160.2 | 9.5682 |
| 900 | 54.143 | 3856.9 | 4398.3 | 10.8429 | 10.8280 | 3856.8 | 4398.2 | 10.1000 | 5.4137 | 3856.7 | 4398.0 | 9.7800 |
| 1000 | 58.758 | 4055.3 | 4642.8 | 11.0429 | 11.7513 | 4055.2 | 4642.7 | 10.3000 | 5.8755 | 4055.0 | 4642.6 | 9.9800 |
| 1100 | 63.373 | 4260.0 | 4893.8 | 11.2326 | 12.6745 | 4259.9 | 4893.7 | 10.4897 | 6.3372 | 4259.8 | 4893.6 | 10.1698 |
| 1200 | 67.989 | 4470.9 | 5150.8 | 11.4132 | 13.5977 | 4470.8 | 5150.7 | 10.6704 | 6.7988 | 4470.7 | 5150.6 | 10.3504 |
| 1300 | 72.604 | 4687.4 | 5413.4 | 11.5857 | 14.5209 | 4687.3 | 5413.3 | 10.8429 | 7.2605 | 4687.2 | 5413.3 | 10.5229 |
| | P = 0.20 MPa (120.21°C) | | | | P = 0.30 MPa (133.52°C) | | | | P = 0.40 MPa (143.61°C) | | | |
| Sat. | 0.88578 | 2529.1 | 2706.3 | 7.1270 | 0.60582 | 2543.2 | 2724.9 | 6.9917 | 0.46242 | 2553.1 | 2738.1 | 6.8955 |
| 150 | 0.95986 | 2577.1 | 2769.1 | 7.2810 | 0.63402 | 2571.0 | 2761.2 | 7.0792 | 0.47088 | 2564.4 | 2752.8 | 6.9306 |
| 200 | 1.08049 | 2654.6 | 2870.7 | 7.5081 | 0.71643 | 2651.0 | 2865.9 | 7.3132 | 0.53434 | 2647.2 | 2860.9 | 7.1723 |
| 250 | 1.19890 | 2731.4 | 2971.2 | 7.7100 | 0.79645 | 2728.9 | 2967.9 | 7.5180 | 0.59520 | 2726.4 | 2964.5 | 7.3804 |
| 300 | 1.31623 | 2808.8 | 3072.1 | 7.8941 | 0.87535 | 2807.0 | 3069.6 | 7.7037 | 0.65489 | 2805.1 | 3067.1 | 7.5677 |
| 400 | 1.54934 | 2967.2 | 3277.0 | 8.2236 | 1.03155 | 2966.0 | 3275.5 | 8.0347 | 0.77265 | 2964.9 | 3273.9 | 7.9003 |
| 500 | 1.78142 | 3131.4 | 3487.7 | 8.5153 | 1.18672 | 3130.6 | 3486.6 | 8.3271 | 0.88936 | 3129.8 | 3485.5 | 8.1933 |
| 600 | 2.01302 | 3302.2 | 3704.8 | 8.7793 | 1.34139 | 3301.6 | 3704.0 | 8.5915 | 1.00558 | 3301.0 | 3703.3 | 8.4580 |
| 700 | 2.24434 | 3479.9 | 3928.8 | 9.0221 | 1.49580 | 3479.5 | 3928.2 | 8.8345 | 1.12152 | 3479.0 | 3927.6 | 8.7012 |
| 800 | 2.47550 | 3664.7 | 4159.8 | 9.2479 | 1.65004 | 3664.3 | 4159.3 | 9.0605 | 1.23730 | 3663.9 | 4158.9 | 8.9274 |
| 900 | 2.70656 | 3856.3 | 4397.7 | 9.4598 | 1.80417 | 3856.0 | 4397.3 | 9.2725 | 1.35298 | 3855.7 | 4396.9 | 9.1394 |
| 1000 | 2.93755 | 4054.8 | 4642.3 | 9.6599 | 1.95824 | 4054.5 | 4642.0 | 9.4726 | 1.46859 | 4054.3 | 4641.7 | 9.3396 |
| 1100 | 3.16848 | 4259.6 | 4893.3 | 9.8497 | 2.11226 | 4259.4 | 4893.1 | 9.6624 | 1.58414 | 4259.2 | 4892.9 | 9.5295 |
| 1200 | 3.39938 | 4470.5 | 5150.4 | 10.0304 | 2.26624 | 4470.3 | 5150.2 | 9.8431 | 1.69966 | 4470.2 | 5150.0 | 9.7102 |
| 1300 | 3.63026 | 4687.1 | 5413.1 | 10.2029 | 2.42019 | 4686.9 | 5413.0 | 10.0157 | 1.81516 | 4686.7 | 5412.8 | 9.8828 |
| | P = 0.50 MPa (151.83°C) | | | | P = 0.60 MPa (158.83°C) | | | | P = 0.80 MPa (170.41°C) | | | |
| Sat. | 0.37483 | 2560.7 | 2748.1 | 6.8207 | 0.31560 | 2566.8 | 2756.2 | 6.7593 | 0.24035 | 2576.0 | 2768.3 | 6.6616 |
| 200 | 0.42503 | 2643.3 | 2855.8 | 7.0610 | 0.35212 | 2639.4 | 2850.6 | 6.9683 | 0.26088 | 2631.1 | 2839.8 | 6.8177 |
| 250 | 0.47443 | 2723.8 | 2961.0 | 7.2725 | 0.39390 | 2721.2 | 2957.6 | 7.1833 | 0.29321 | 2715.9 | 2950.4 | 7.0402 |
| 300 | 0.52261 | 2803.3 | 3064.6 | 7.4614 | 0.43442 | 2801.4 | 3062.0 | 7.3740 | 0.32416 | 2797.5 | 3056.9 | 7.2345 |
| 350 | 0.57015 | 2883.0 | 3168.1 | 7.6346 | 0.47428 | 2881.6 | 3166.1 | 7.5481 | 0.35442 | 2878.6 | 3162.2 | 7.4107 |
| 400 | 0.61731 | 2963.7 | 3272.4 | 7.7956 | 0.51374 | 2962.5 | 3270.8 | 7.7097 | 0.38429 | 2960.2 | 3267.7 | 7.5735 |
| 500 | 0.71095 | 3129.0 | 3484.5 | 8.0893 | 0.59200 | 3128.2 | 3483.4 | 8.0041 | 0.44332 | 3126.6 | 3481.3 | 7.8692 |
| 600 | 0.80409 | 3300.4 | 3702.5 | 8.3544 | 0.66976 | 3299.8 | 3701.7 | 8.2695 | 0.50186 | 3298.7 | 3700.1 | 8.1354 |
| 700 | 0.89696 | 3478.6 | 3927.0 | 8.5978 | 0.74725 | 3478.1 | 3926.4 | 8.5132 | 0.56011 | 3477.2 | 3925.3 | 8.3794 |
| 800 | 0.98966 | 3663.6 | 4158.4 | 8.8240 | 0.82457 | 3663.2 | 4157.9 | 8.7395 | 0.61820 | 3662.5 | 4157.0 | 8.6061 |
| 900 | 1.08227 | 3855.4 | 4396.6 | 9.0362 | 0.90179 | 3855.1 | 4396.2 | 8.9518 | 0.67619 | 3854.5 | 4395.5 | 8.8185 |
| 1000 | 1.17480 | 4054.0 | 4641.4 | 9.2364 | 0.97893 | 4053.8 | 4641.1 | 9.1521 | 0.73411 | 4053.3 | 4640.5 | 9.0189 |
| 1100 | 1.26728 | 4259.0 | 4892.6 | 9.4263 | 1.05603 | 4258.8 | 4892.4 | 9.3420 | 0.79197 | 4258.3 | 4891.9 | 9.2090 |
| 1200 | 1.35972 | 4470.0 | 5149.8 | 9.6071 | 1.13309 | 4469.8 | 5149.6 | 9.5229 | 0.84980 | 4469.4 | 5149.3 | 9.3898 |
| 1300 | 1.45214 | 4686.6 | 5412.6 | 9.7797 | 1.21012 | 4686.4 | 5412.5 | 9.6955 | 0.90761 | 4686.1 | 5412.2 | 9.5625 |

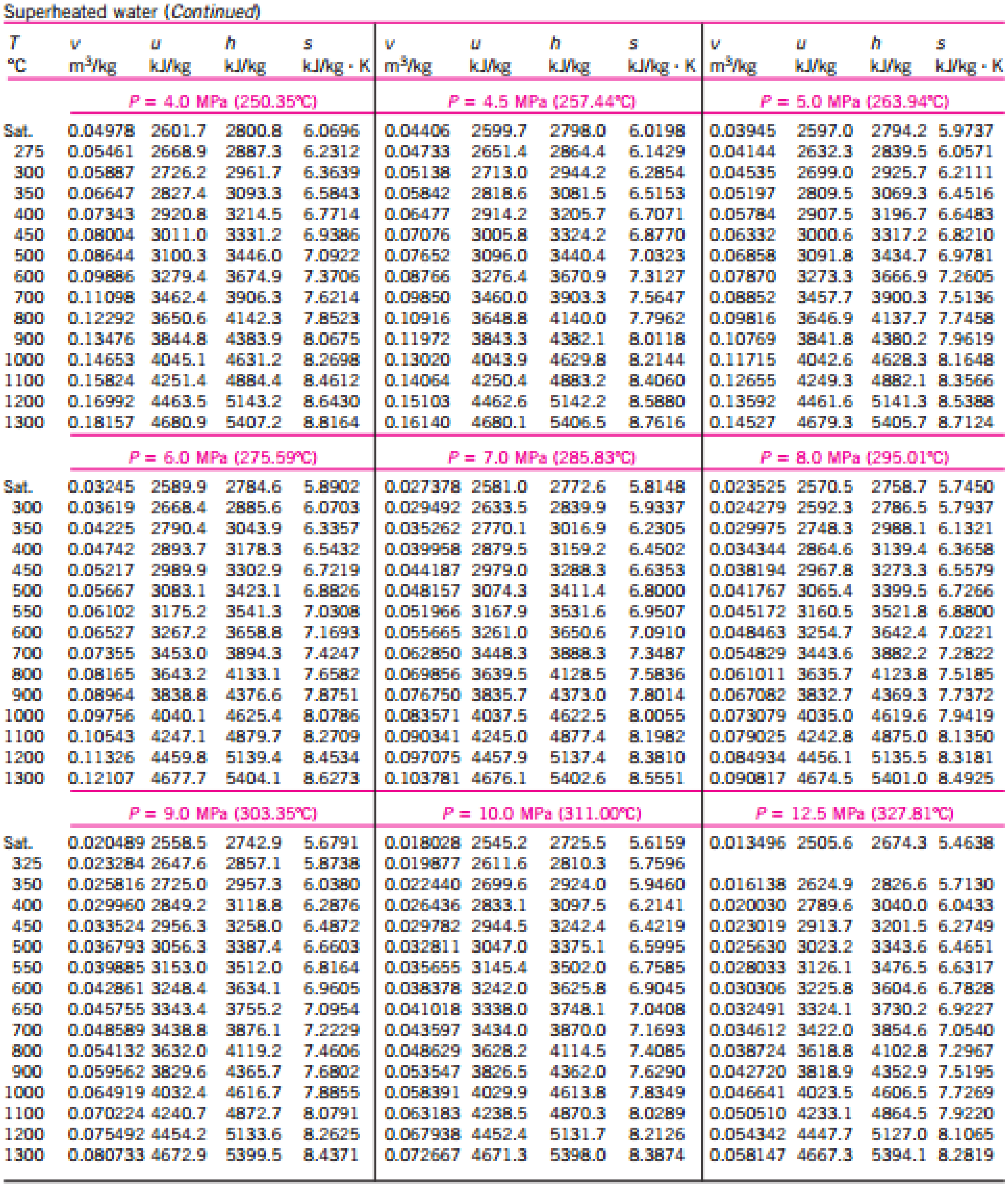
**Table 5. Super-heated water table**



Superheated water (*Continued*)

| $T$ °C | $v$ m³/kg | $u$ kJ/kg | $h$ kJ/kg | $s$ kJ/kg · K | $v$ m³/kg | $u$ kJ/kg | $h$ kJ/kg | $s$ kJ/kg · K | $v$ m³/kg | $u$ kJ/kg | $h$ kJ/kg | $s$ kJ/kg · K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $P$ = 1.00 MPa (179.88°C) | | | | $P$ = 1.20 MPa (187.96°C) | | | | $P$ = 1.40 MPa (195.04°C) | | | |
| Sat. | 0.19437 | 2582.8 | 2777.1 | 6.5850 | 0.16326 | 2587.8 | 2783.8 | 6.5217 | 0.14078 | 2591.8 | 2788.9 | 6.4675 |
| 200 | 0.20602 | 2622.3 | 2828.3 | 6.6956 | 0.16934 | 2612.9 | 2816.1 | 6.5909 | 0.14303 | 2602.7 | 2803.0 | 6.4975 |
| 250 | 0.23275 | 2710.4 | 2943.1 | 6.9265 | 0.19241 | 2704.7 | 2935.6 | 6.8313 | 0.16356 | 2698.9 | 2927.9 | 6.7488 |
| 300 | 0.25799 | 2793.7 | 3051.6 | 7.1246 | 0.21386 | 2789.7 | 3046.3 | 7.0335 | 0.18233 | 2785.7 | 3040.9 | 6.9553 |
| 350 | 0.28250 | 2875.7 | 3158.2 | 7.3029 | 0.23455 | 2872.7 | 3154.2 | 7.2139 | 0.20029 | 2869.7 | 3150.1 | 7.1379 |
| 400 | 0.30661 | 2957.9 | 3264.5 | 7.4670 | 0.25482 | 2955.5 | 3261.3 | 7.3793 | 0.21782 | 2953.1 | 3258.1 | 7.3046 |
| 500 | 0.35411 | 3125.0 | 3479.1 | 7.7642 | 0.29464 | 3123.4 | 3477.0 | 7.6779 | 0.25216 | 3121.8 | 3474.8 | 7.6047 |
| 600 | 0.40111 | 3297.5 | 3698.6 | 8.0311 | 0.33395 | 3296.3 | 3697.0 | 7.9456 | 0.28597 | 3295.1 | 3695.5 | 7.8730 |
| 700 | 0.44783 | 3476.3 | 3924.1 | 8.2755 | 0.37297 | 3475.3 | 3922.9 | 8.1904 | 0.31951 | 3474.4 | 3921.7 | 8.1183 |
| 800 | 0.49438 | 3661.7 | 4156.1 | 8.5024 | 0.41184 | 3661.0 | 4155.2 | 8.4176 | 0.35288 | 3660.3 | 4154.3 | 8.3458 |
| 900 | 0.54083 | 3853.9 | 4394.8 | 8.7150 | 0.45059 | 3853.3 | 4394.0 | 8.6303 | 0.38614 | 3852.7 | 4393.3 | 8.5587 |
| 1000 | 0.58721 | 4052.7 | 4640.0 | 8.9155 | 0.48928 | 4052.2 | 4639.4 | 8.8310 | 0.41933 | 4051.7 | 4638.8 | 8.7595 |
| 1100 | 0.63354 | 4257.9 | 4891.4 | 9.1057 | 0.52792 | 4257.5 | 4891.0 | 9.0212 | 0.45247 | 4257.0 | 4890.5 | 8.9497 |
| 1200 | 0.67983 | 4469.0 | 5148.9 | 9.2866 | 0.56652 | 4468.7 | 5148.5 | 9.2022 | 0.48558 | 4468.3 | 5148.1 | 9.1308 |
| 1300 | 0.72610 | 4685.8 | 5411.9 | 9.4593 | 0.60509 | 4685.5 | 5411.6 | 9.3750 | 0.51866 | 4685.1 | 5411.3 | 9.3036 |
| | $P$ = 1.60 MPa (201.37°C) | | | | $P$ = 1.80 MPa (207.11°C) | | | | $P$ = 2.00 MPa (212.38°C) | | | |
| Sat. | 0.12374 | 2594.8 | 2792.8 | 6.4200 | 0.11037 | 2597.3 | 2795.9 | 6.3775 | 0.09959 | 2599.1 | 2798.3 | 6.3390 |
| 225 | 0.13293 | 2645.1 | 2857.8 | 6.5537 | 0.11678 | 2637.0 | 2847.2 | 6.4825 | 0.10381 | 2628.5 | 2836.1 | 6.4160 |
| 250 | 0.14190 | 2692.9 | 2919.9 | 6.6753 | 0.12502 | 2686.7 | 2911.7 | 6.6088 | 0.11150 | 2680.3 | 2903.3 | 6.5475 |
| 300 | 0.15866 | 2781.6 | 3035.4 | 6.8864 | 0.14025 | 2777.4 | 3029.9 | 6.8246 | 0.12551 | 2773.2 | 3024.2 | 6.7684 |
| 350 | 0.17459 | 2866.6 | 3146.0 | 7.0713 | 0.15460 | 2863.6 | 3141.9 | 7.0120 | 0.13860 | 2860.5 | 3137.7 | 6.9583 |
| 400 | 0.19007 | 2950.8 | 3254.9 | 7.2394 | 0.16849 | 2948.3 | 3251.6 | 7.1814 | 0.15122 | 2945.9 | 3248.4 | 7.1292 |
| 500 | 0.22029 | 3120.1 | 3472.6 | 7.5410 | 0.19551 | 3118.5 | 3470.4 | 7.4845 | 0.17568 | 3116.9 | 3468.3 | 7.4337 |
| 600 | 0.24999 | 3293.9 | 3693.9 | 7.8101 | 0.22200 | 3292.7 | 3692.3 | 7.7543 | 0.19962 | 3291.5 | 3690.7 | 7.7043 |
| 700 | 0.27941 | 3473.5 | 3920.5 | 8.0558 | 0.24822 | 3472.6 | 3919.4 | 8.0005 | 0.22326 | 3471.7 | 3918.2 | 7.9509 |
| 800 | 0.30865 | 3659.5 | 4153.4 | 8.2834 | 0.27426 | 3658.8 | 4152.4 | 8.2284 | 0.24674 | 3658.0 | 4151.5 | 8.1791 |
| 900 | 0.33780 | 3852.1 | 4392.6 | 8.4965 | 0.30020 | 3851.5 | 4391.9 | 8.4417 | 0.27012 | 3850.9 | 4391.1 | 8.3925 |
| 1000 | 0.36687 | 4051.2 | 4638.2 | 8.6974 | 0.32606 | 4050.7 | 4637.6 | 8.6427 | 0.29342 | 4050.2 | 4637.1 | 8.5936 |
| 1100 | 0.39589 | 4256.6 | 4890.0 | 8.8878 | 0.35188 | 4256.2 | 4889.6 | 8.8331 | 0.31667 | 4255.7 | 4889.1 | 8.7842 |
| 1200 | 0.42488 | 4467.9 | 5147.7 | 9.0689 | 0.37766 | 4467.6 | 5147.3 | 9.0143 | 0.33989 | 4467.2 | 5147.0 | 8.9654 |
| 1300 | 0.45383 | 4684.8 | 5410.9 | 9.2418 | 0.40341 | 4684.5 | 5410.6 | 9.1872 | 0.36308 | 4684.2 | 5410.3 | 9.1384 |
| | $P$ = 2.50 MPa (223.95°C) | | | | $P$ = 3.00 MPa (233.85°C) | | | | $P$ = 3.50 MPa (242.56°C) | | | |
| Sat. | 0.07995 | 2602.1 | 2801.9 | 6.2558 | 0.06667 | 2603.2 | 2803.2 | 6.1856 | 0.05706 | 2603.0 | 2802.7 | 6.1244 |
| 225 | 0.08026 | 2604.8 | 2805.5 | 6.2629 | | | | | | | | |
| 250 | 0.08705 | 2663.3 | 2880.9 | 6.4107 | 0.07063 | 2644.7 | 2856.5 | 6.2893 | 0.05876 | 2624.0 | 2829.7 | 6.1764 |
| 300 | 0.09894 | 2762.2 | 3009.6 | 6.6459 | 0.08118 | 2750.8 | 2994.3 | 6.5412 | 0.06845 | 2738.8 | 2978.4 | 6.4484 |
| 350 | 0.10979 | 2852.5 | 3127.0 | 6.8424 | 0.09056 | 2844.4 | 3116.1 | 6.7450 | 0.07680 | 2836.0 | 3104.9 | 6.6601 |
| 400 | 0.12012 | 2939.8 | 3240.1 | 7.0170 | 0.09938 | 2933.6 | 3231.7 | 6.9235 | 0.08456 | 2927.2 | 3223.2 | 6.8428 |
| 450 | 0.13015 | 3026.2 | 3351.6 | 7.1768 | 0.10789 | 3021.2 | 3344.9 | 7.0856 | 0.09198 | 3016.1 | 3338.1 | 7.0074 |
| 500 | 0.13999 | 3112.8 | 3462.8 | 7.3254 | 0.11620 | 3108.6 | 3457.2 | 7.2359 | 0.09919 | 3104.5 | 3451.7 | 7.1593 |
| 600 | 0.15931 | 3288.5 | 3686.8 | 7.5979 | 0.13245 | 3285.5 | 3682.8 | 7.5103 | 0.11325 | 3282.5 | 3678.9 | 7.4357 |
| 700 | 0.17835 | 3469.3 | 3915.2 | 7.8455 | 0.14841 | 3467.0 | 3912.2 | 7.7590 | 0.12702 | 3464.7 | 3909.3 | 7.6855 |
| 800 | 0.19722 | 3656.2 | 4149.2 | 8.0744 | 0.16420 | 3654.3 | 4146.9 | 7.9885 | 0.14061 | 3652.5 | 4144.6 | 7.9156 |
| 900 | 0.21597 | 3849.4 | 4389.3 | 8.2882 | 0.17988 | 3847.9 | 4387.5 | 8.2028 | 0.15410 | 3846.4 | 4385.7 | 8.1304 |
| 1000 | 0.23466 | 4049.0 | 4635.6 | 8.4897 | 0.19549 | 4047.7 | 4634.2 | 8.4045 | 0.16751 | 4046.4 | 4632.7 | 8.3324 |
| 1100 | 0.25330 | 4254.7 | 4887.9 | 8.6804 | 0.21105 | 4253.6 | 4886.7 | 8.5955 | 0.18087 | 4252.5 | 4885.6 | 8.5236 |
| 1200 | 0.27190 | 4466.3 | 5146.0 | 8.8618 | 0.22658 | 4465.3 | 5145.1 | 8.7771 | 0.19420 | 4464.4 | 5144.1 | 8.7053 |
| 1300 | 0.29048 | 4683.4 | 5409.5 | 9.0349 | 0.24207 | 4682.6 | 5408.8 | 8.9502 | 0.20750 | 4681.8 | 5408.0 | 8.8786 |

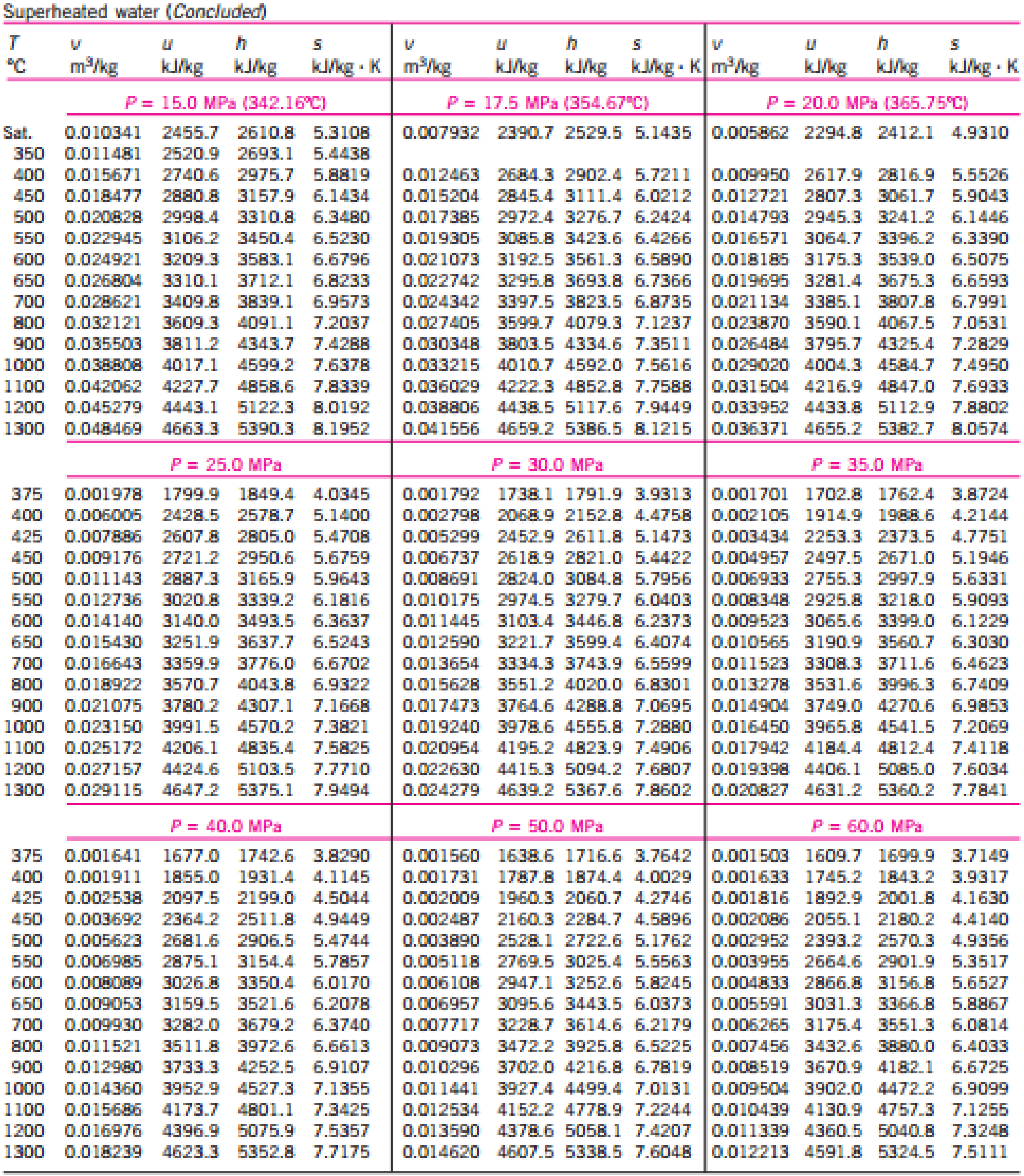
**Table 6. Super-heated water table (continued)**



Superheated water (*Continued*)

| $T$ °C | $v$ m$^3$/kg | $u$ kJ/kg | $h$ kJ/kg | $s$ kJ/kg · K | $v$ m$^3$/kg | $u$ kJ/kg | $h$ kJ/kg | $s$ kJ/kg · K | $v$ m$^3$/kg | $u$ kJ/kg | $h$ kJ/kg | $s$ kJ/kg · K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $P$ = 4.0 MPa (250.35°C) | | | | $P$ = 4.5 MPa (257.44°C) | | | | $P$ = 5.0 MPa (263.94°C) | | | |
| Sat. | 0.04978 | 2601.7 | 2800.8 | 6.0696 | 0.04406 | 2599.7 | 2798.0 | 6.0198 | 0.03945 | 2597.0 | 2794.2 | 5.9737 |
| 275 | 0.05461 | 2668.9 | 2887.3 | 6.2312 | 0.04733 | 2651.4 | 2864.4 | 6.1429 | 0.04144 | 2632.3 | 2839.5 | 6.0571 |
| 300 | 0.05887 | 2726.2 | 2961.7 | 6.3639 | 0.05138 | 2713.0 | 2944.2 | 6.2854 | 0.04535 | 2699.0 | 2925.7 | 6.2111 |
| 350 | 0.06647 | 2827.4 | 3093.3 | 6.5843 | 0.05842 | 2818.6 | 3081.5 | 6.5153 | 0.05197 | 2809.5 | 3069.3 | 6.4516 |
| 400 | 0.07343 | 2920.8 | 3214.5 | 6.7714 | 0.06477 | 2914.2 | 3205.7 | 6.7071 | 0.05784 | 2907.5 | 3196.7 | 6.6483 |
| 450 | 0.08004 | 3011.0 | 3331.2 | 6.9386 | 0.07076 | 3005.8 | 3324.2 | 6.8770 | 0.06332 | 3000.6 | 3317.2 | 6.8210 |
| 500 | 0.08644 | 3100.3 | 3446.0 | 7.0922 | 0.07652 | 3096.0 | 3440.4 | 7.0323 | 0.06858 | 3091.8 | 3434.7 | 6.9781 |
| 600 | 0.09886 | 3279.4 | 3674.9 | 7.3706 | 0.08766 | 3276.4 | 3670.9 | 7.3127 | 0.07870 | 3273.3 | 3666.9 | 7.2605 |
| 700 | 0.11098 | 3462.4 | 3906.3 | 7.6214 | 0.09850 | 3460.0 | 3903.3 | 7.5647 | 0.08852 | 3457.7 | 3900.3 | 7.5136 |
| 800 | 0.12292 | 3650.6 | 4142.3 | 7.8523 | 0.10916 | 3648.8 | 4140.0 | 7.7962 | 0.09816 | 3646.9 | 4137.7 | 7.7458 |
| 900 | 0.13476 | 3844.8 | 4383.9 | 8.0675 | 0.11972 | 3843.3 | 4382.1 | 8.0118 | 0.10769 | 3841.8 | 4380.2 | 7.9619 |
| 1000 | 0.14653 | 4045.1 | 4631.2 | 8.2698 | 0.13020 | 4043.9 | 4629.8 | 8.2144 | 0.11715 | 4042.6 | 4628.3 | 8.1648 |
| 1100 | 0.15824 | 4251.4 | 4884.4 | 8.4612 | 0.14064 | 4250.4 | 4883.2 | 8.4060 | 0.12655 | 4249.3 | 4882.1 | 8.3566 |
| 1200 | 0.16992 | 4463.5 | 5143.2 | 8.6430 | 0.15103 | 4462.6 | 5142.2 | 8.5880 | 0.13592 | 4461.6 | 5141.3 | 8.5388 |
| 1300 | 0.18157 | 4680.9 | 5407.2 | 8.8164 | 0.16140 | 4680.1 | 5406.5 | 8.7616 | 0.14527 | 4679.3 | 5405.7 | 8.7124 |
| | $P$ = 6.0 MPa (275.59°C) | | | | $P$ = 7.0 MPa (285.83°C) | | | | $P$ = 8.0 MPa (295.01°C) | | | |
| Sat. | 0.03245 | 2589.9 | 2784.6 | 5.8902 | 0.027378 | 2581.0 | 2772.6 | 5.8148 | 0.023525 | 2570.5 | 2758.7 | 5.7450 |
| 300 | 0.03619 | 2668.4 | 2885.6 | 6.0703 | 0.029492 | 2633.5 | 2839.9 | 5.9337 | 0.024279 | 2592.3 | 2786.5 | 5.7937 |
| 350 | 0.04225 | 2790.4 | 3043.9 | 6.3357 | 0.035262 | 2770.1 | 3016.9 | 6.2305 | 0.029975 | 2748.3 | 2988.1 | 6.1321 |
| 400 | 0.04742 | 2893.7 | 3178.3 | 6.5432 | 0.039958 | 2879.5 | 3159.2 | 6.4502 | 0.034344 | 2864.6 | 3139.4 | 6.3658 |
| 450 | 0.05217 | 2989.9 | 3302.9 | 6.7219 | 0.044187 | 2979.0 | 3288.3 | 6.6353 | 0.038194 | 2967.8 | 3273.3 | 6.5579 |
| 500 | 0.05667 | 3083.1 | 3423.1 | 6.8826 | 0.048157 | 3074.3 | 3411.4 | 6.8000 | 0.041767 | 3065.4 | 3399.5 | 6.7266 |
| 550 | 0.06102 | 3175.2 | 3541.3 | 7.0308 | 0.051966 | 3167.9 | 3531.6 | 6.9507 | 0.045172 | 3160.5 | 3521.8 | 6.8800 |
| 600 | 0.06527 | 3267.2 | 3658.8 | 7.1693 | 0.055665 | 3261.0 | 3650.6 | 7.0910 | 0.048463 | 3254.7 | 3642.4 | 7.0221 |
| 700 | 0.07355 | 3453.0 | 3894.3 | 7.4247 | 0.062850 | 3448.3 | 3888.3 | 7.3487 | 0.054829 | 3443.6 | 3882.2 | 7.2822 |
| 800 | 0.08165 | 3643.2 | 4133.1 | 7.6582 | 0.069856 | 3639.5 | 4128.5 | 7.5836 | 0.061011 | 3635.7 | 4123.8 | 7.5185 |
| 900 | 0.08964 | 3838.8 | 4376.6 | 7.8751 | 0.076750 | 3835.7 | 4373.0 | 7.8014 | 0.067082 | 3832.7 | 4369.3 | 7.7372 |
| 1000 | 0.09756 | 4040.1 | 4625.4 | 8.0786 | 0.083571 | 4037.5 | 4622.5 | 8.0055 | 0.073079 | 4035.0 | 4619.6 | 7.9419 |
| 1100 | 0.10543 | 4247.1 | 4879.7 | 8.2709 | 0.090341 | 4245.0 | 4877.4 | 8.1982 | 0.079025 | 4242.8 | 4875.0 | 8.1350 |
| 1200 | 0.11326 | 4459.8 | 5139.4 | 8.4534 | 0.097075 | 4457.9 | 5137.4 | 8.3810 | 0.084934 | 4456.1 | 5135.5 | 8.3181 |
| 1300 | 0.12107 | 4677.7 | 5404.1 | 8.6273 | 0.103781 | 4676.1 | 5402.6 | 8.5551 | 0.090817 | 4674.5 | 5401.0 | 8.4925 |
| | $P$ = 9.0 MPa (303.35°C) | | | | $P$ = 10.0 MPa (311.00°C) | | | | $P$ = 12.5 MPa (327.81°C) | | | |
| Sat. | 0.020489 | 2558.5 | 2742.9 | 5.6791 | 0.018028 | 2545.2 | 2725.5 | 5.6159 | 0.013496 | 2505.6 | 2674.3 | 5.4638 |
| 325 | 0.023284 | 2647.6 | 2857.1 | 5.8738 | 0.019877 | 2611.6 | 2810.3 | 5.7596 | | | | |
| 350 | 0.025816 | 2725.0 | 2957.3 | 6.0380 | 0.022440 | 2699.6 | 2924.0 | 5.9460 | 0.016138 | 2624.9 | 2826.6 | 5.7130 |
| 400 | 0.029960 | 2849.2 | 3118.8 | 6.2876 | 0.026436 | 2833.1 | 3097.5 | 6.2141 | 0.020030 | 2789.6 | 3040.0 | 6.0433 |
| 450 | 0.033524 | 2956.3 | 3258.0 | 6.4872 | 0.029782 | 2944.5 | 3242.4 | 6.4219 | 0.023019 | 2913.7 | 3201.5 | 6.2749 |
| 500 | 0.036793 | 3056.3 | 3387.4 | 6.6603 | 0.032811 | 3047.0 | 3375.1 | 6.5995 | 0.025630 | 3023.2 | 3343.6 | 6.4651 |
| 550 | 0.039885 | 3153.0 | 3512.0 | 6.8164 | 0.035655 | 3145.4 | 3502.0 | 6.7585 | 0.028033 | 3126.1 | 3476.5 | 6.6317 |
| 600 | 0.042861 | 3248.4 | 3634.1 | 6.9605 | 0.038378 | 3242.0 | 3625.8 | 6.9045 | 0.030306 | 3225.8 | 3604.6 | 6.7828 |
| 650 | 0.045755 | 3343.4 | 3755.2 | 7.0954 | 0.041018 | 3338.0 | 3748.1 | 7.0408 | 0.032491 | 3324.1 | 3730.2 | 6.9227 |
| 700 | 0.048589 | 3438.8 | 3876.1 | 7.2229 | 0.043597 | 3434.0 | 3870.0 | 7.1693 | 0.034612 | 3422.0 | 3854.6 | 7.0540 |
| 800 | 0.054132 | 3632.0 | 4119.2 | 7.4606 | 0.048629 | 3628.2 | 4114.5 | 7.4085 | 0.038724 | 3618.8 | 4102.8 | 7.2967 |
| 900 | 0.059562 | 3829.6 | 4365.7 | 7.6802 | 0.053547 | 3826.5 | 4362.0 | 7.6290 | 0.042720 | 3818.9 | 4352.9 | 7.5195 |
| 1000 | 0.064919 | 4032.4 | 4616.7 | 7.8855 | 0.058391 | 4029.9 | 4613.8 | 7.8349 | 0.046641 | 4023.5 | 4606.5 | 7.7269 |
| 1100 | 0.070224 | 4240.7 | 4872.7 | 8.0791 | 0.063183 | 4238.5 | 4870.3 | 8.0289 | 0.050510 | 4233.1 | 4864.5 | 7.9220 |
| 1200 | 0.075492 | 4454.2 | 5133.6 | 8.2625 | 0.067938 | 4452.4 | 5131.7 | 8.2126 | 0.054342 | 4447.7 | 5127.0 | 8.1065 |
| 1300 | 0.080733 | 4672.9 | 5399.5 | 8.4371 | 0.072667 | 4671.3 | 5398.0 | 8.3874 | 0.058147 | 4667.3 | 5394.1 | 8.2819 |

**Table 7. Super-heated water table (continued)**

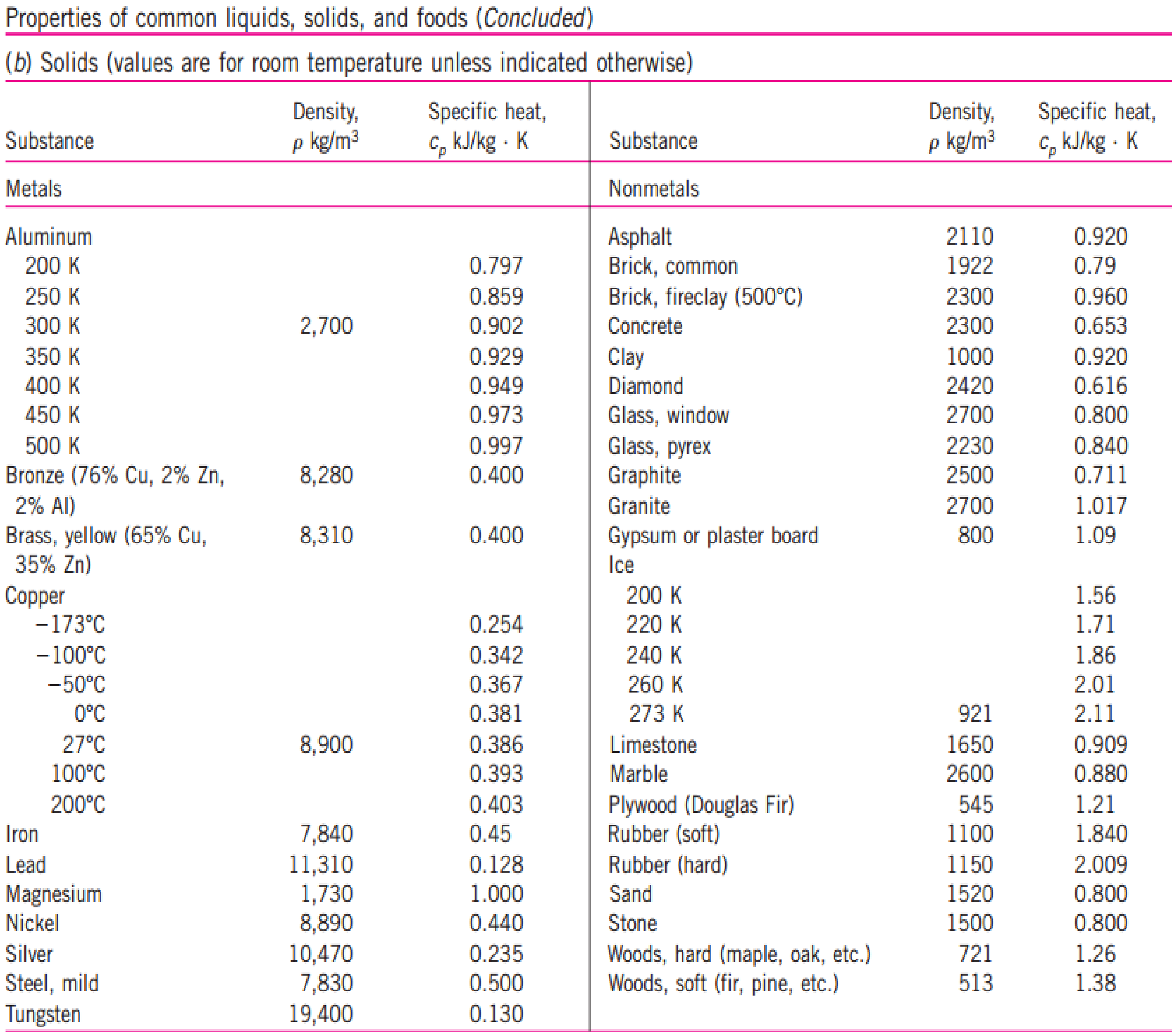


Superheated water (*Concluded*)

| *T* °C | *v* $m^3$/kg | *u* kJ/kg | *h* kJ/kg | *s* kJ/kg · K | *v* $m^3$/kg | *u* kJ/kg | *h* kJ/kg | *s* kJ/kg · K | *v* $m^3$/kg | *u* kJ/kg | *h* kJ/kg | *s* kJ/kg · K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *P* = 15.0 MPa (342.16°C) | | | | *P* = 17.5 MPa (354.67°C) | | | | *P* = 20.0 MPa (365.75°C) | | | |
| Sat. | 0.010341 | 2455.7 | 2610.8 | 5.3108 | 0.007932 | 2390.7 | 2529.5 | 5.1435 | 0.005862 | 2294.8 | 2412.1 | 4.9310 |
| 350 | 0.011481 | 2520.9 | 2693.1 | 5.4438 | | | | | | | | |
| 400 | 0.015671 | 2740.6 | 2975.7 | 5.8819 | 0.012463 | 2684.3 | 2902.4 | 5.7211 | 0.009950 | 2617.9 | 2816.9 | 5.5526 |
| 450 | 0.018477 | 2880.8 | 3157.9 | 6.1434 | 0.015204 | 2845.4 | 3111.4 | 6.0212 | 0.012721 | 2807.3 | 3061.7 | 5.9043 |
| 500 | 0.020828 | 2998.4 | 3310.8 | 6.3480 | 0.017385 | 2972.4 | 3276.7 | 6.2424 | 0.014793 | 2945.3 | 3241.2 | 6.1446 |
| 550 | 0.022945 | 3106.2 | 3450.4 | 6.5230 | 0.019305 | 3085.8 | 3423.6 | 6.4266 | 0.016571 | 3064.7 | 3396.2 | 6.3390 |
| 600 | 0.024921 | 3209.3 | 3583.1 | 6.6796 | 0.021073 | 3192.5 | 3561.3 | 6.5890 | 0.018185 | 3175.3 | 3539.0 | 6.5075 |
| 650 | 0.026804 | 3310.1 | 3712.1 | 6.8233 | 0.022742 | 3295.8 | 3693.8 | 6.7366 | 0.019695 | 3281.4 | 3675.3 | 6.6593 |
| 700 | 0.028621 | 3409.8 | 3839.1 | 6.9573 | 0.024342 | 3397.5 | 3823.5 | 6.8735 | 0.021134 | 3385.1 | 3807.8 | 6.7991 |
| 800 | 0.032121 | 3609.3 | 4091.1 | 7.2037 | 0.027405 | 3599.7 | 4079.3 | 7.1237 | 0.023870 | 3590.1 | 4067.5 | 7.0531 |
| 900 | 0.035503 | 3811.2 | 4343.7 | 7.4288 | 0.030348 | 3803.5 | 4334.6 | 7.3511 | 0.026484 | 3795.7 | 4325.4 | 7.2829 |
| 1000 | 0.038808 | 4017.1 | 4599.2 | 7.6378 | 0.033215 | 4010.7 | 4592.0 | 7.5616 | 0.029020 | 4004.3 | 4584.7 | 7.4950 |
| 1100 | 0.042062 | 4227.7 | 4858.6 | 7.8339 | 0.036029 | 4222.3 | 4852.8 | 7.7588 | 0.031504 | 4216.9 | 4847.0 | 7.6933 |
| 1200 | 0.045279 | 4443.1 | 5122.3 | 8.0192 | 0.038806 | 4438.5 | 5117.6 | 7.9449 | 0.033952 | 4433.8 | 5112.9 | 7.8802 |
| 1300 | 0.048469 | 4663.3 | 5390.3 | 8.1952 | 0.041556 | 4659.2 | 5386.5 | 8.1215 | 0.036371 | 4655.2 | 5382.7 | 8.0574 |
| | *P* = 25.0 MPa | | | | *P* = 30.0 MPa | | | | *P* = 35.0 MPa | | | |
| 375 | 0.001978 | 1799.9 | 1849.4 | 4.0345 | 0.001792 | 1738.1 | 1791.9 | 3.9313 | 0.001701 | 1702.8 | 1762.4 | 3.8724 |
| 400 | 0.006005 | 2428.5 | 2578.7 | 5.1400 | 0.002798 | 2068.9 | 2152.8 | 4.4758 | 0.002105 | 1914.9 | 1988.6 | 4.2144 |
| 425 | 0.007886 | 2607.8 | 2805.0 | 5.4708 | 0.005299 | 2452.9 | 2611.8 | 5.1473 | 0.003434 | 2253.3 | 2373.5 | 4.7751 |
| 450 | 0.009176 | 2721.2 | 2950.6 | 5.6759 | 0.006737 | 2618.9 | 2821.0 | 5.4422 | 0.004957 | 2497.5 | 2671.0 | 5.1946 |
| 500 | 0.011143 | 2887.3 | 3165.9 | 5.9643 | 0.008691 | 2824.0 | 3084.8 | 5.7956 | 0.006933 | 2755.3 | 2997.9 | 5.6331 |
| 550 | 0.012736 | 3020.8 | 3339.2 | 6.1816 | 0.010175 | 2974.5 | 3279.7 | 6.0403 | 0.008348 | 2925.8 | 3218.0 | 5.9093 |
| 600 | 0.014140 | 3140.0 | 3493.5 | 6.3637 | 0.011445 | 3103.4 | 3446.8 | 6.2373 | 0.009523 | 3065.6 | 3399.0 | 6.1229 |
| 650 | 0.015430 | 3251.9 | 3637.7 | 6.5243 | 0.012590 | 3221.7 | 3599.4 | 6.4074 | 0.010565 | 3190.9 | 3560.7 | 6.3030 |
| 700 | 0.016643 | 3359.9 | 3776.0 | 6.6702 | 0.013654 | 3334.3 | 3743.9 | 6.5599 | 0.011523 | 3308.3 | 3711.6 | 6.4623 |
| 800 | 0.018922 | 3570.7 | 4043.8 | 6.9322 | 0.015628 | 3551.2 | 4020.0 | 6.8301 | 0.013278 | 3531.6 | 3996.3 | 6.7409 |
| 900 | 0.021075 | 3780.2 | 4307.1 | 7.1668 | 0.017473 | 3764.6 | 4288.8 | 7.0695 | 0.014904 | 3749.0 | 4270.6 | 6.9853 |
| 1000 | 0.023150 | 3991.5 | 4570.2 | 7.3821 | 0.019240 | 3978.6 | 4555.8 | 7.2880 | 0.016450 | 3965.8 | 4541.5 | 7.2069 |
| 1100 | 0.025172 | 4206.1 | 4835.4 | 7.5825 | 0.020954 | 4195.2 | 4823.9 | 7.4906 | 0.017942 | 4184.4 | 4812.4 | 7.4118 |
| 1200 | 0.027157 | 4424.6 | 5103.5 | 7.7710 | 0.022630 | 4415.3 | 5094.2 | 7.6807 | 0.019398 | 4406.1 | 5085.0 | 7.6034 |
| 1300 | 0.029115 | 4647.2 | 5375.1 | 7.9494 | 0.024279 | 4639.2 | 5367.6 | 7.8602 | 0.020827 | 4631.2 | 5360.2 | 7.7841 |
| | *P* = 40.0 MPa | | | | *P* = 50.0 MPa | | | | *P* = 60.0 MPa | | | |
| 375 | 0.001641 | 1677.0 | 1742.6 | 3.8290 | 0.001560 | 1638.6 | 1716.6 | 3.7642 | 0.001503 | 1609.7 | 1699.9 | 3.7149 |
| 400 | 0.001911 | 1855.0 | 1931.4 | 4.1145 | 0.001731 | 1787.8 | 1874.4 | 4.0029 | 0.001633 | 1745.2 | 1843.2 | 3.9317 |
| 425 | 0.002538 | 2097.5 | 2199.0 | 4.5044 | 0.002009 | 1960.3 | 2060.7 | 4.2746 | 0.001816 | 1892.9 | 2001.8 | 4.1630 |
| 450 | 0.003692 | 2364.2 | 2511.8 | 4.9449 | 0.002487 | 2160.3 | 2284.7 | 4.5896 | 0.002086 | 2055.1 | 2180.2 | 4.4140 |
| 500 | 0.005623 | 2681.6 | 2906.5 | 5.4744 | 0.003890 | 2528.1 | 2722.6 | 5.1762 | 0.002952 | 2393.2 | 2570.3 | 4.9356 |
| 550 | 0.006985 | 2875.1 | 3154.4 | 5.7857 | 0.005118 | 2769.5 | 3025.4 | 5.5563 | 0.003955 | 2664.6 | 2901.9 | 5.3517 |
| 600 | 0.008089 | 3026.8 | 3350.4 | 6.0170 | 0.006108 | 2947.1 | 3252.6 | 5.8245 | 0.004833 | 2866.8 | 3156.8 | 5.6527 |
| 650 | 0.009053 | 3159.5 | 3521.6 | 6.2078 | 0.006957 | 3095.6 | 3443.5 | 6.0373 | 0.005591 | 3031.3 | 3366.8 | 5.8867 |
| 700 | 0.009930 | 3282.0 | 3679.2 | 6.3740 | 0.007717 | 3228.7 | 3614.6 | 6.2179 | 0.006265 | 3175.4 | 3551.3 | 6.0814 |
| 800 | 0.011521 | 3511.8 | 3972.6 | 6.6613 | 0.009073 | 3472.2 | 3925.8 | 6.5225 | 0.007456 | 3432.6 | 3880.0 | 6.4033 |
| 900 | 0.012980 | 3733.3 | 4252.5 | 6.9107 | 0.010296 | 3702.0 | 4216.8 | 6.7819 | 0.008519 | 3670.9 | 4182.1 | 6.6725 |
| 1000 | 0.014360 | 3952.9 | 4527.3 | 7.1355 | 0.011441 | 3927.4 | 4499.4 | 7.0131 | 0.009504 | 3902.0 | 4472.2 | 6.9099 |
| 1100 | 0.015686 | 4173.7 | 4801.1 | 7.3425 | 0.012534 | 4152.2 | 4778.9 | 7.2244 | 0.010439 | 4130.9 | 4757.3 | 7.1255 |
| 1200 | 0.016976 | 4396.9 | 5075.9 | 7.5357 | 0.013590 | 4378.6 | 5058.1 | 7.4207 | 0.011339 | 4360.5 | 5040.8 | 7.3248 |
| 1300 | 0.018239 | 4623.3 | 5352.8 | 7.7175 | 0.014620 | 4607.5 | 5338.5 | 7.6048 | 0.012213 | 4591.8 | 5324.5 | 7.5111 |

**Table 8. Super-heated water table (continued)**

# Appendix D



Properties of common liquids, solids, and foods (*Concluded*)

(*b*) Solids (values are for room temperature unless indicated otherwise)

| Substance | Density, $\rho$ kg/m$^3$ | Specific heat, $c_p$ kJ/kg · K | Substance | Density, $\rho$ kg/m$^3$ | Specific heat, $c_p$ kJ/kg · K |
|---|---|---|---|---|---|
| Metals | | | Nonmetals | | |
| Aluminum | | | Asphalt | 2110 | 0.920 |
| 200 K | | 0.797 | Brick, common | 1922 | 0.79 |
| 250 K | | 0.859 | Brick, fireclay (500°C) | 2300 | 0.960 |
| 300 K | 2,700 | 0.902 | Concrete | 2300 | 0.653 |
| 350 K | | 0.929 | Clay | 1000 | 0.920 |
| 400 K | | 0.949 | Diamond | 2420 | 0.616 |
| 450 K | | 0.973 | Glass, window | 2700 | 0.800 |
| 500 K | | 0.997 | Glass, pyrex | 2230 | 0.840 |
| Bronze (76% Cu, 2% Zn, | 8,280 | 0.400 | Graphite | 2500 | 0.711 |
| 2% Al) | | | Granite | 2700 | 1.017 |
| Brass, yellow (65% Cu, | 8,310 | 0.400 | Gypsum or plaster board | 800 | 1.09 |
| 35% Zn) | | | Ice | | |
| Copper | | | 200 K | | 1.56 |
| −173°C | | 0.254 | 220 K | | 1.71 |
| −100°C | | 0.342 | 240 K | | 1.86 |
| −50°C | | 0.367 | 260 K | | 2.01 |
| 0°C | | 0.381 | 273 K | 921 | 2.11 |
| 27°C | 8,900 | 0.386 | Limestone | 1650 | 0.909 |
| 100°C | | 0.393 | Marble | 2600 | 0.880 |
| 200°C | | 0.403 | Plywood (Douglas Fir) | 545 | 1.21 |
| Iron | 7,840 | 0.45 | Rubber (soft) | 1100 | 1.840 |
| Lead | 11,310 | 0.128 | Rubber (hard) | 1150 | 2.009 |
| Magnesium | 1,730 | 1.000 | Sand | 1520 | 0.800 |
| Nickel | 8,890 | 0.440 | Stone | 1500 | 0.800 |
| Silver | 10,470 | 0.235 | Woods, hard (maple, oak, etc.) | 721 | 1.26 |
| Steel, mild | 7,830 | 0.500 | Woods, soft (fir, pine, etc.) | 513 | 1.38 |
| Tungsten | 19,400 | 0.130 | | | |

**Table 9. Properties of common materials**

# Appendix E

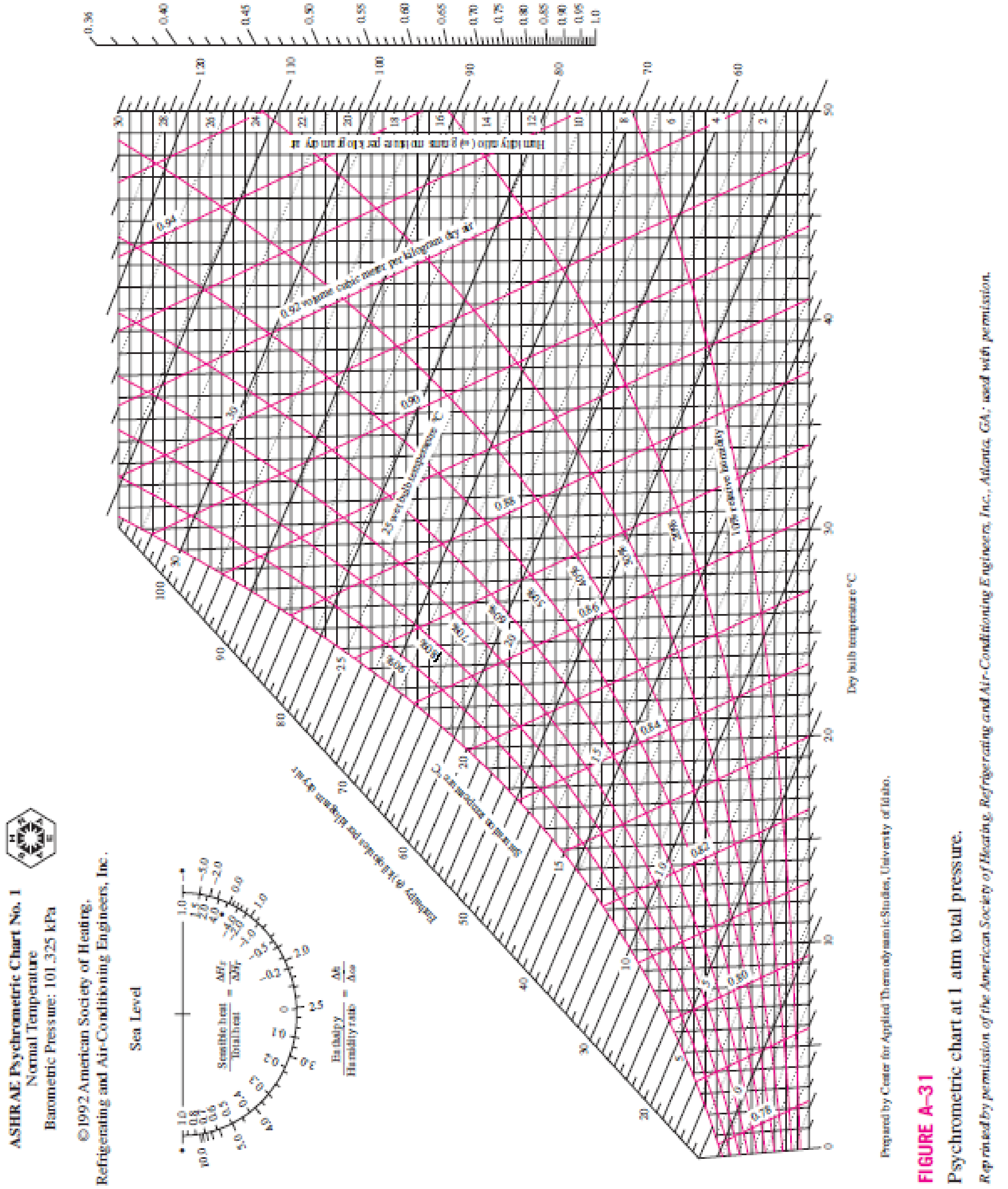


**Table 10. Psychometric chart at one atmosphere**