EVALUATION AND OPTIMIZATION OF EFFICIENCY OF POWER PLANTS

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ABSTRACT

Power generation is one of most vital topics currently; therefore there have been a lot of studies on this topic ranging from fossil energy sources to solar and nuclear energies. However high demand on fossil fuels need to come to a stop due to all the destructive effects. The amount of energy loss in power plants which use fossil fuels is quite high. Hence most of these studies also include new methods to minimize these energy losses as much as possible. In this research, studies have been conducted in order to improve the efficiency of Kish gas power plant which is located in Iran. The primary objectives of this study are analyzing the system component separate1y and based on the understanding achieved, methods is suggested to avoid energy losses as well as producing more output work. Performance of the plant was estimated by component-wise modeling and a detail break-up of the inlet and output of each part of power plant components. As per the analysis, the power output of Kish power plant which has seven turbines is 25 MW without losses through condenser. Two boilers and a condenser have the major role in the power output and according to analysis boiler and condenser are main part of this study in order to see the effect of pressure and temperature on Rankin cycle which is the main modelling used to achieve the objectives.

ABSTRAK

Penjanaan kuasa adalah salah satu topik paling penting pada masa ini; oleh itu terdapat banyak kajian mengenai topik ini dari sumber tenaga fosil kepada tenaga solar dan nuklear. Walau bagaimanapun permintaan yang tinggi terhadap bahan api fosil perlu dihentikan kerana semua kesan merosakkan. Jumlah kehilangan tenaga di loji kuasa yang menggunakan bahan api fosil agak tinggi. Oleh itu kebanyakan kajian ini juga termasuk kaedah baru untuk meminimumkan kehilangan tenaga sebanyak mungkin. Dalam kajian ini, kajian telah dijalankan untuk meningkatkan kecekapan loji kuasa gas Kish yang terletak di Iran. Objektif utama kajian ini adalah menganalisis komponen sistem berasingan1 dan berdasarkan pemahaman yang dicapai, kaedah-kaedah yang dicadangkan untuk mengelakkan kehilangan tenaga serta menghasilkan lebih banyak kerja bersih. Prestasi kilang itu dianggarkan oleh pemodelan yang bijak komponen dan pemisahan terperinci kemasukan dan keluaran setiap bahagian komponen loji janakuasa. Mengikut analisis, output tenaga kilang kuasa Kish yang mempunyai tujuh turbin adalah 25 MW tanpa kehilangan melalui kondenser. Dua dandang dan kondenser mempunyai peranan utama dalam pengeluaran kuasa dan menurut analisis dandang dan pemeluwap adalah bahagian utama kajian ini untuk melihat kesan tekanan dan suhu pada kitar Rankin yang merupakan pemodelan utama yang digunakan untuk mencapai matlamat.

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LIST OF SYMBOLS AND ABBREVIATIONS

FWH	:	Feedwater Heater
OFWH	:	Open Feedwater Heater
CFWH	:	Close Feedwater Heater
RPM	:	Revolutions per minute
RC	:	Rankine Cycle
kW	:	Kilowatt
MW	:	Megawatt
kPa	:	Kilopascal
psia	:	Pounds per Square Inch Absolute
T-S	:	Temperature vs. Specific Entropy Diagram
EES	:	Engineering Equation Software

CHAPTER 1: INTRODUCTION

1.1 Background

The major energy source being used today's world are fossil fuels such as oil, natural gas and fossil fuels. They have become one of the most vital parts of life, and almost every industry is directly or indirectly impacted by them. We depend on them to generate heat, run machines, and vehicles, deliver power and electricity to our factories and keep our manufacturing and production alive and running.

However, our reliance on fossil fuels must eventually decline as their availability has been decreasing dramatically. Currently, due to less availability of fossil fuels, the cost of extracting them has been increased which is creating a considerable problem as this increment in their cost directly increase the price of almost everything, hence impacting people's living expenses. On the other hands, there have been numerous debates about not using fossil fuels due to their disadvantages such as non- renewable, environmental hazards, effects on price fluctuations, overdependence, human health, impact on aquatic life, in need of huge reserves, disastrous accidents and so on.

Electricity is generated by powering up massive turbines by burning fossil fuels such as coal, oil or gas and turning them into steam. There are lots of power plants in every country all around the world which, for a long period of time, more or less has been using the same basic concept for producing electricity reliably. Unfortunately burning these fossil fuels generate a great quantity of Carbon Dioxide which causes climate change.

Almost 80% of the electricity generated in today's world is dependent on fossil fuels which have to turn the electrical power generation into a concerning issue. However, there are other sources of energy such as renewable energies which include Wind Power, Solar, Biomass, Hydrogen and fuel cells, Geothermal power, Hydroelectric energy and so on and they all more or less rely on sunlight. Renewable energy is replenished energy which is obtained from the natural resources. The best prospective renewable energy resource is Solar thermal power.

A number of nations still rely on non-renewable nuclear fuels and fossil fuels for electricity generation, but number of countries are focusing and prioritizing the renewable energy sources as the sources of fossil fuels are running out and within the general public the awareness is growing about the negative impact of burning fossil fuels on the environment. Although it is not easy to replace fossil fuels, it will be wise to start developing and investing more in renewable energies to be able to replace them eventually.

Unfortunately, this transition is not easy, and when it comes to third world countries, it can be even harder as less availability of renewable technologies. On the other hand, fossil fuels are the main source of economy in some countries such as Middle Eastern countries. As a result of this derivative and limited access to newer technologies prevent them from adapting to renewable energies.

So the focus in these countries is mostly on maintenance and increasing the efficiency of their power plants. For example, Iran is a third world country which is under a lot of sanctions and maintenance and improving the efficiency of their existing power plants is the most vital issue. Moreover, they have limited access to spare parts; hence there is a huge demand for improving the power plants using the existing equipment available. Due to this, there are lots of research and studies to improve the efficiency of power plants by using the available technologies and tools which makes it very hard.

1.2 Problem Statement

In this research, Kish Power Plant in Iran has been studied. Iran is one of the main and most important oil and gas producers in the world, and its economy and power generation is dangerously dependent on fossil fuels. Iran has remained a big consumer of fossil fuel energy and their consumption of fossil fuel energy reported to be at 98.99% in 2014, the report was published and generated by World Bank through different development indicators, which were compiled by officially recognized sources.

In some third world countries such as Iran, it is either expensive or impossible to have access to the latest power generation technologies. Despite this, there has been a great push by Iranian scientists to conduct studies about renewable energies but accessing the latest technology is quite difficult for them.

Unfortunately, due to heavy sanctions imposed on Iran, purchase of new equipment for power plants has become a difficult challenge, and the cost of their maintenance has increased subsequently. So the only option is to improve what's already there. For example, Kish gas power plant is quite large, but equipment being used are rather aged which leads to a significant energy loss. This has motivated a lot of studies to be conducted in order to improve the efficiency of the existing power plants by using available technologies and equipment at hand. This is main motivation that has driven this research project as well.

1.3 Objective

The primary objective of this research is to:

1. Analyze the system components of a power plant separately and
2. Through several simulations quantify the elements that can develop a certain method(s) to increase the power plant efficiency.

Meaning, the primary goal is to find a method to have more power generated with lower energy losses. The performance of the power plant could be estimated by component-wise modeling and a detailed break-up of the inlet and output of each part of Power Plant components and it will be later enhanced according to the initial estimations.

Objectives of this research are to calculate input and output of each unit of Kish power plant. Then according to this information, suggestions will be made in order to improve the efficiency of this power plant by following Rankine Cycle modelling principles and enhancing its parameters.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In this chapter studies and reviews have been conducted on the relative papers and similar systems to achieve a better understanding of power plants and particularly gas power plants' architecture. Additionally, feedwater heater which is the most important component of this project has also been studied as well as Rankine cycle which is the primary method used in this project to achieve better efficiency.

2.2 Gas Power Plant

These power plants use natural gas combined with combusted steam to generate electricity by spinning the turbines. The advantages of using natural gas compared to other dominant fuel sources such as coal and oil are the lower cost and much less pollution caused by burning it.

Gas power plants can be divided into two types:

1. Simple Cycle Gas Plants
2. Combined Cycle Gas Plants

Combined Cycle Gas Plants are far more efficient compared to Simple Cycle Power Plants. While the first one is used for fulfilling the electricity needs of the society, the later makes use of the hot exhaust gases that are created that would otherwise be dispelled from the system. This way, the efficiency would increase as these exhaust gases can be used to start another turbine and generate more electricity.

The combined cycle thermal efficiency can be obtained up to 60%. These thermal plants produce about 33% of the waste heat of a plant with the same efficiency. The cost incurred by the use of combined cycle plants is mostly higher as the build and run cost is more in it. The cost estimated by EIA for a simple cycle plant is about US$389/kW, whereas combined cycle plants are US$500 – 550/kW.

There are several studies on gas power plants in order to find ways to improve the efficiency. In a paper published by Manuel Valdez and Dolores Duran in 2003, it is suggested to use a generic algorithm which has been tuned applying it to a single pressure Combined Cycle Gas Plant in order achieve a thermos-economic optimization (Valdés & Durán, 2003). The overall cost would be a lot if the only purpose of the design would be to improve the thermodynamic efficiency, so it is wiser to compromise between efficiency and cost.

2.3 Feedwater Heater (FWH)

There are several components in gas power plants such as turbines, condensers, boilers, pumps, feedwater heaters and so on; however, the most important one which has been studied in details in this project is feedwater heater.

Feedwater heaters are used to pre-heat water which is delivered to boilers so that boilers use less energy to heat water. So the main objective of feedwater heaters is to increase the thermodynamic efficiency of the system. There are two types of feedwater heaters:

1. Open Feedwater Heater (OFWH)
2. Closed Feedwater Heater (CFWH)

The first one has direct contact with water, and it blends steam and water inside the chamber. However the latter allows the water passes through it while heating the water by the steam inside the chamber.

As discussed, the main model used in this project is a Rankine cycle, and in gas power plants which use modified Rankine cycle modelling, feed-water heaters allow the feed-water to be brought up very gradually to the saturation temperature. This reduces the inevitable irreversibility's linked with water heat transfer.

There have been several studies regarding using feedwater heaters in the design of power plants in order improve efficiency. According to the result of these studies, most of the energy losses happen at the boiler and during the heating process, and these losses can be noticeably omitted by using feedwater heaters (Farhad & Younessi-Sinaki, 2008; Habib & Zubair, 1991; Gupta & Kaushik, 2009).

In a paper published by Habib and Zubair in 1991, using feedwater heater in a Rankine cycle modelled gas power plant resulted in 12% improvement in efficiency. Their design is based on the second law of thermodynamics, and according to a simple logic that is, the performance of such power plants can be enhanced with the decrease in temperature at which the heat is rejected to the surroundings and by increasing the extreme temperature at which heat is transferred to water (Habib & Zubair, 1991).

In most of the studies on this topic, the designs are according to the first law of thermos-dynamics without considering the irreversibilities concept and sometimes based on the second law of thermodynamics. However, in a paper published by Siamak Farhad and Maryam Younessi-Sinaki in 2007, the Pinch technology was used. The Pinch technology is an efficient and simple tool for combined design of heat exchange networks. This method, however, has effects on all components of the system. Hence a powerful tool must have been used in order to predict the irreversibilities in all components accurately (Farhad & Younessi-Sinaki, 2008). As a result, Exergy analysis was used to determine the performance changes.

2.4 Rankine Cycle (RC)

Rankine cycle is a model used in power plants such as gas power plants in to predict and advance the performance of system. It is a thermodynamic cycle with idealized efficiency of heat engine which typically converts heat to the mechanical work which undergoes a phase change. The supply of heat is made externally by closed loop, which consumes water as working fluid. Simply, the concept is that water or water vapor (steam) should be cycled and reused constantly.

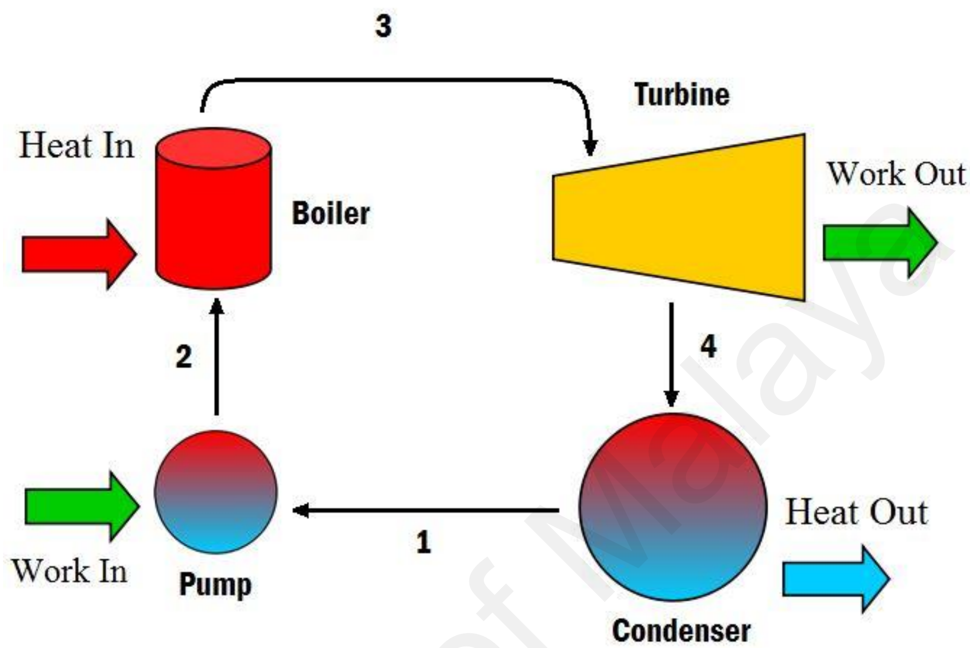

Figure 1 Rankine Cycle Steps

Currently, the most effective energy conversion technology is the arrangement of a gas turbine with a steam turbine bottoming cycle (Franco & Casarosa, 2002).

The main differences between Rankine cycles and steam cycles are in:

- Superheating
- Low Temperature Heat Recovery
- Components Size
- Boiler Design

- Turbine Inlet Temperature
- Pump Consumption
- High Pressure
- Condensing Pressure
- Fluid Characteristic
- Turbine Design
- Efficiency

This modelling is used in many power plants and there have been lots of researches around this topic. In a paper published by Donghong Wei, Xuesheng Lu, Zhen Lu and Jianming Gu in 2006, it was determined that the wasted heat from power plants is around $370°C$ which is a large amount of wasted heat which is economically infeasible and it can cause lots of environmental pollution. However by using Rankine cycle which provides flexibility and low maintenance (Wei & Lu, 2006). Integrating the Rankine cycle to the energy system, such as achieving a low grade energy (waste heat) to generate high grade energy (power), power plants, improving the system efficiency and easing the power burden and.

There have been other methods used to replace Rankine cycle such as Novel Bottoming Cycle which is even more efficient. However it can cause instability in the system (Kalina, 2009).

CHAPTER 3: METHODOLOGY

3.1 Introduction

In this chapter, the methodology used during the development of the system is identified. The system components are explained in details, and the method and modelling used to achieve system efficiency are discussed.

According to chapter 2, Rankine cycle modelling has been used in this chapter to improve the efficiency of the system, and best usage of feedwater heater in the system has also been determined.

3.2 Steam Power Plant

Steam Power Plant is a Thermal Power plant through which water is converted to steam with the use of high temperature. This high temperature is used to generate electricity by rotating the turbine at a required RPM. The steam power consists of a number of components for the conversion of mechanical energy to electrical energy. The components used in the conversion process include a condenser, boiler, re-heater, high and low pressure turbine, feedwater pump, economizer, super heater, feedwater heater and so on. The thermal efficiency of the process increased by using the steam power plant which uses the atmospheric air and through it into the pre-heater by flue gas. The boiler absorbs the heated air and fuel for the combustion process then water converted to steam and the moisture is removed by the use of super-heater.

A high pressure steam turbine then takes the steam into it afterward the steam is heated again and passed to the low pressure turbine; this connection has used an alternative for electricity generation. At this level, condenser absorbs the steam and it is converted into the water and then moved to the feedwater heater and further moved to the economizer to make the water available for reuse and sends it to the boiler for cycling process. The principle of Rankine cycle is used by the thermal power plant as shown in the figure below:

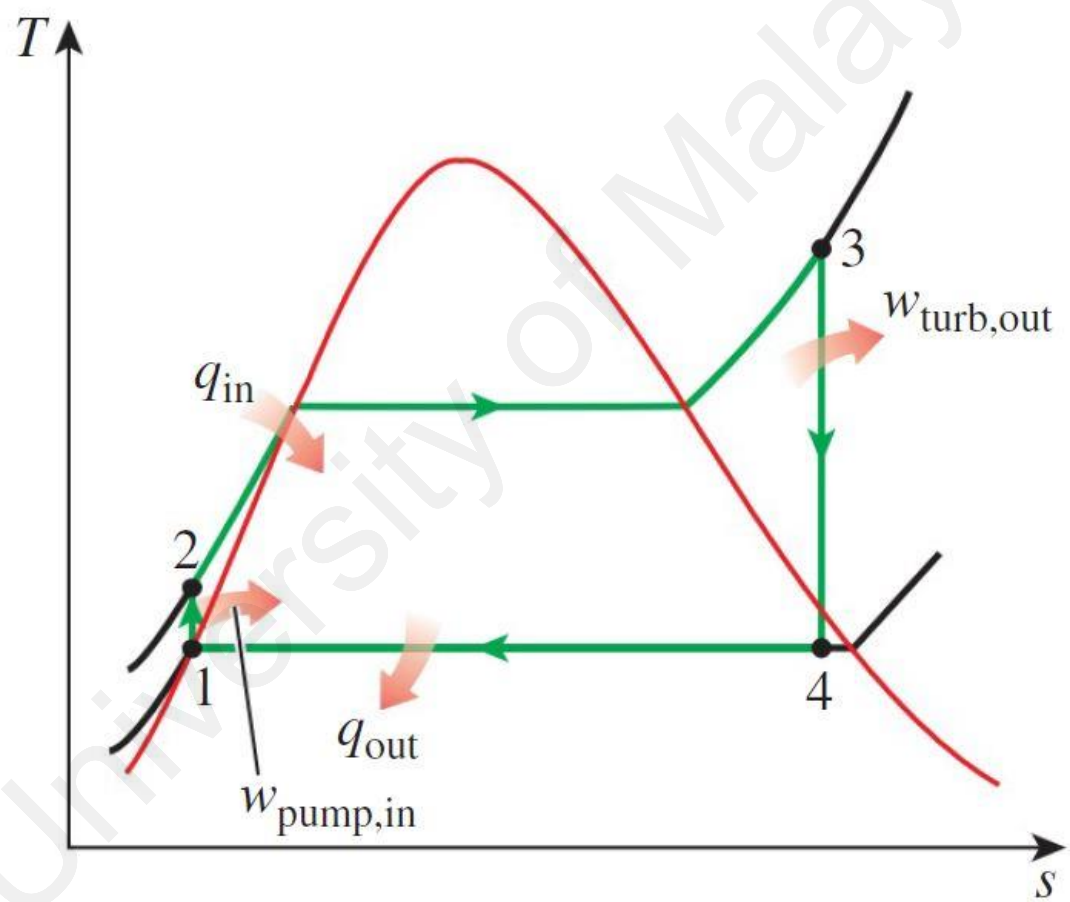

Figure 2 Principle of Rankine Cycle

The Ranking cycle process follows the four procedures:

(1-2) Isentropic compression in the pump;

(2-3) Constant pressure heat addition in a boiler;

(3-4) Isentropic expansion in a turbine;

(4-1) Constant pressure heat rejection in a condenser;

Some factors like super-heating the steam using high temperature, lowering the pressure of condenser, regenerate Rankine cycle or reheating the Rankine cycle in which feed-water heated from extracted steam are used to improve the complete cycle.

3.2.1 CONDENCERS TYPES

The power plant uses two major types of condensers which are:

1. Direct Contact
2. Surface

A direct contact condenser used to condense the steam exhausted from turbine then mix it with the cooling water. The Jet type condensers and an older type Barometric work on the same principles. The modern power plants commonly use the steam surface condensers. The steam exhausted from the turbine move into the shell side of the condenser, while the circulating water in the plant moves into the tube side. The circulating water generated from either once through (i.e., from rive, ocean or lake) or from the closed loop (i.e., spray pond, cooling tower, etc.). The steam condensed in the turbine is called condensate, collected in the bottom of the condenser, which is called a hot well. For the repetition cycle, the condensate from this process pumped back into the steam generator.

A. Condenser Types Steam Surface Condenser Operation

The surface condenser's main heat transferring process involves the condensing of soaked steam which comes from the outside of the tubes while the circulating water is heated from the inside the tubes. Therefore, for the flow rate of given circulating water, the pressure condenser determined by the water inlet temperature, the condenser pressure decrease with the decrease in water inlet temperature. As explained previously, the plant output efficiency is increased with the decrease in the pressure. The fact here is the surface condenser works under vacuum, the gasses which are not condensed will move to the condenser. In this process, the gases which are non-condensable are usually the air which moved from the components working at lower atmospheric pressure (as the condenser). These gases are generated through thermal chemical reaction by which the water decomposed into hydrogen and oxygen. These gases emitted from the condenser due to the given reasons:

The condenser's operating pressure increase by these gases. As the total pressure of the condenser is the addition of the gases and the partial pressure of steam, the condenser pressure will increase when more gas seeped into the system. The turbine efficiency will decrease with the increase in pressure. The outer surface of tubes will be blanketed by the gases. This process will decrease the heat transfer of steam severely to the circulating water.

B. Stem Surface Condenser Air Removal

The two major components used for the venting of non-condensable gases include the Liquid Ring Vacuum pumps and Jet Air Ejectors. A high pressure motive steam is used by the Steam Jet Air Ejectors for the evacuation of non-condensable from the condenser (Jet Pump).

The evacuated non-condensable is compressed by the liquid Ring Vacuum Pumps an then it discharged the non-condensable to the atmospheric air. The condensers are furnished with an Air-Cooler for the removal of non-condensable gases.

The Air- Cooler unit condenser contains a number of tubes which are mystified to accumulate the non-condensable. The size of air removal equipment and its volume is reduced by the cooling of non-condensable. The air removal equipment work in two methods: hogging and holding. All the non-condensable vented from the condenser before the admission exhaust steam to the condenser. At the hogging method, the condenser pressure reduced from atmospheric to the defined level when large air volume is removed from the condenser. When the system attained the required pressure in holding method, the air removal system starts working to remove the non-condensable gases.

C. Steam Surface Condenser Configuration

At a broader level, stream surface condenser characterized by the alignment of the exhausting turbine to the condenser. The commonly used are the down and side exhaust. The exhaust condenser used to install the turbine and condenser adjacent to each other, then the turbine's steam enters from the side of the condenser. In down exhaust condenser, steam enters from the turbine go from the top of the condenser and the turbine is mounted on a fountain above the condenser.

The configuration of tube sides and the shell then delineate the condenser. The tube side of steam condenser further classified as:

The configuration of water boxes and tube bundles pass by the number of tubes. There are either single or multiple tube side possessed by most of the steam surface condensers. The frequency of circulating water along the length of the condenser with in the tubes define the number of passes. A once-through circulating water system with condensers is mostly one pass. A closed loop system is normally used for the multiple pass condenser.

The classification of tube side system is either divided or non-divided. The water boxes and tube bundles are divided into sections in the divided condensers. A single or multiple tube sections are in working conditions while others are not. In the working time of condenser, these tube sections allow them the maintenance of sections. The other tube side which is not divided, the tubes remain in working condition continuously. The steam surface condenser's shell side categorized by its geometry. Its examples are:

- Cylindrical
- Rectangular

The above configuration is chosen after defining the manufacturer preference, size of the condenser and plant layout. The steam surface condenser could be a multiple pressure or multiple shell configuration as well.

3.3 Effect of System Component on Efficiency

In the world, the production of electric power is mostly determined by the steam power plant. Sometime it provides a lot of savings in fuel consumption when the thermal system is efficiently working. Therefore, the improvement in efficiency of the steam power plant prioritizes with the maximum effort. Heat transferred to the working fluid when the average temperature of the boiler is increased, or the average temperature of working fluid in the condenser is decreased at which heat is rejected. So that the average temperature of fluid should be high at heat addition and it must be kept at a lowest possible level during the heat rejection. In the next level, this study discusses three ways of completing this by simple ideal Rankine cycle.

Due to irreversibility in different components the deal Rankine cycle is different from the actual vapor power cycle. The irreversibility is done by two main sources which include heat loss and fluid friction process. The boiler pressure in different components of piping and condenser drops due to fluid friction. This results in steam left the boiler at little lower pressure. Moreover, the drop of pressure in connecting pipes brings the turbine inlet pressure little lower than the pressure at the boiler exit. Usually, there is a minimal decrease in the pressure of condenser. The water here is pumped to a much higher pressure than the ideal requirement for the compensation of the pressure drop; this needs a larger work input to pumps and large pumps. The loss of heat from steam to the surroundings is also the major source of irreversibility as the steam passes to different components. The undesired losses of heat are mitigated by transferring more heat in the boiler which will maintain the desired level of output work. This results in a decrease of cycle efficiency.

3.3.1 Rankine Cycle: The Vapor Power Cycles

The Carnot cycle deficiencies eliminated by the process of super-heating the steam in the boiler and condensing it in the condenser. This all results in providing the ideal cycle for vapor power plants called the Rankine cycle. The perfection of the Rankine cycle involves no internal irreversibility. The Rankine cycle involves following four processes.

1. Isentropic compression in a pump
2. Constant pressure heat addition in a boiler
3. Isentropic expansion in a turbine
4. Constant pressure heat rejection in a condenser

At first level water goes into the pump in the form of saturated liquid and the water then compressed isentropically according to the boiler's pressure. During the isentropic process, the temperature of water increases because of a little reduction in the water volume. At second level the water moves into the boiler in the form of compressed liquid while at third level water leaves as superheated vapor. A large heat is exchanged at the boiler which originates from the combustion of gases, nuclear reactors or other sources which transferred to water at constant pressure of boiler together with the section where steam is superheated, called the steam generator.

From level three the superheated vapor goes into the turbine, where the vapor expands isentropically, and the connected shaft produces work to an electric generator. The steam's temperature and pressure drop under this process and leads to the level four, in which steam goes into the condenser. At this level, steam is a high quality liquid vapor mixture. Constant pressure is required to condense the steam in the condenser, which is a large heat exchanger. This process rejects the heat to enter in the cooling medium like river, lake or outer atmosphere. The cycle is completed by leaving the steam from condenser as a saturated liquid and then goes into the pump. The power plants cooled by the use of air instead of water where the water is valuable for the process. The same cooling method is used for car engines which are called dry cooling. A dry cooling system for water conservation is widely used in a number of plants around the globe.

The process curve on a T-S diagram here explains the internally reversible processes involve the heat transfer. This can be seen in the area under process curve 2-3 which provides the explanation of transfer of heat in the boiler to water. The curve 4-1 explains the rejection of heat by the condenser. The difference between these two (the area enclosed by the cycle curve) is the output work produced during the cycle.

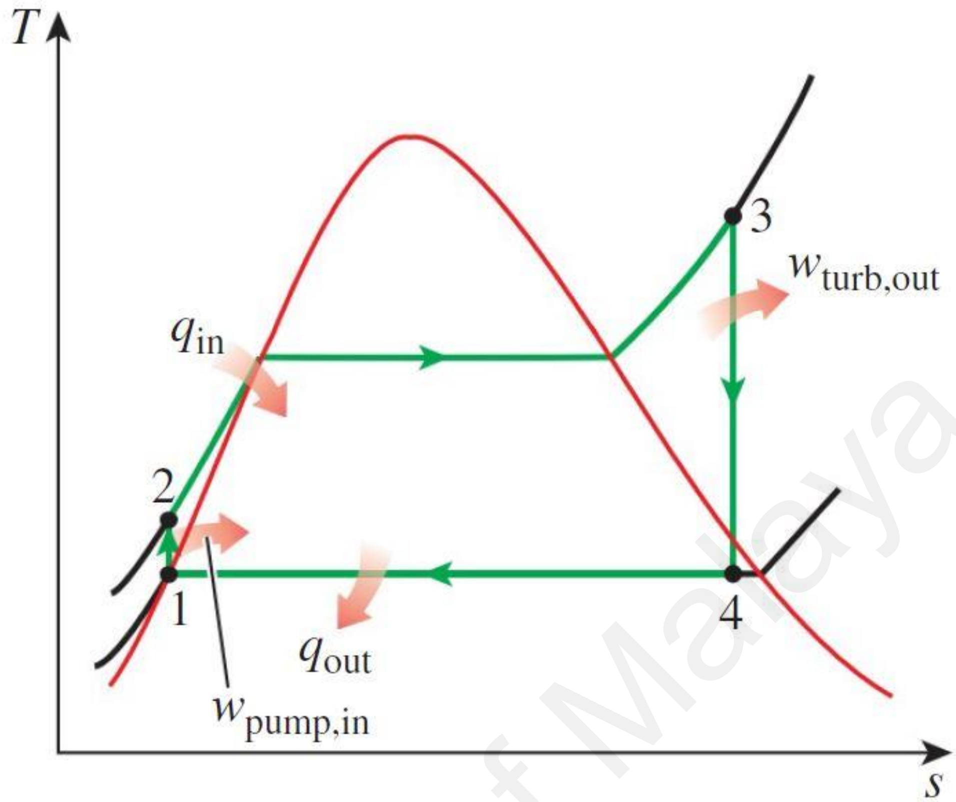

Figure 3 Rankine Cycle States

3.3.2 Energy Analysis of the Ideal Rankine Cycle

The four components linked with the Rankine cycle (the boiler, pump, turbine, and condenser) explain the steady flow process, therefore the four mechanisms of Rankine cycle which explain its process can be assessed by steady flow processes. The potential and kinetic energy changes in the steam process are smaller as compared to the work and heat transfer term and mostly neglected. The equation of steady flow energy explains the mass per unit of steam can be examined by:

$$(q_{in-}q_{out}) + (W_{in-}W_{out}) = h_e - h_i$$

The four components which explain the Rankine cycle (boiler, the pump, condenser, and turbine) as said to be the steady flow devices. Therefore the four mechanisms of Rankine cycle which explain its process can be assessed by steady flow processes. The potential and kinetic energy changes in the steam process are smaller as compared to the work and heat transfer term and mostly neglected. The equation of steady flow energy explains the mass per unit of steam can be reduced to:

$W_{pump} = h_2 - h_1$ Or $W_{pump} = v(p_2 - p_1)$

$Boiler\ (w = 0)$

$q_{in} = h_o - h_i$

$Turbine\ (q = 0)$

$W_{turb-out} = h_o - h_i$

$Condenser\ (w = 0)$

$$q_{out} = h_o - h_i$$

The thermal efficiency of the Rankine cycle is determined from:

$$\eta = \frac{W_{net}}{Q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$W_{net} = W_{turb-out} - W_{pump-in}$$

3.3.3 The Ideal Regenerative Rankine Cycle

A deep analysis of the Rankine cycle stated in T-S diagram discloses that the transfer of heat to the working fluid done at comparatively lower temperature. The process explains that it reduces the average heat addition temperature. Therefore the efficiency of the cycle is affected. To cure this deficiency, here study analyzes the ways which increase the temperature of the liquid leaving the pump (feedwater) before it goes into the boiler. One way is by transferring heat from the expanding steam to the feedwater by building a counter flow of heat exchanger in the turbine, which helps in regeneration. Designing this solution is difficult because at final stages of the process the moisture contents will be increased which make it an impractical model.

An applied process of regeneration in steam power plants could be achieved by the “bleeding” or extraction of steam from the turbine. The expansion of steam in the turbine produces more work which could be used for heating the feedwater instead. A feedwater heater (FWH) or regenerator is used for heating the feedwater. The process of regeneration not only provides convenience to deaerating the feedwater (eliminating the air leakage in the condenser) but also improves the cycle efficiency. The convenience to deaerating the feedwater prevents the boiler from corrosion. It also provides control on the flow rate of steam in the latest stages of the turbine. Thus, almost all the model steam power pants use the regeneration technique since its introduction in the 1920s. The heat is moved from the steam to the feedwater either without mixing the fluid (closed feed-water) or mixing the two fluids (Open feed-water). The next part will discuss the regeneration of both the feedwater heaters types.

3.3.4 Open Feed-water Heater (OFWH)

A mixing chamber where the extracted steam from turbine mixes with the feedwater at the point of pump exit is called an open (direct contact) feedwater heater. The ideal point is reached when the heater pressure makes the mixture to leave the heater. A steam power plant scheme with an open feed water heater (single-stage regenerator) is shown in figure 4:

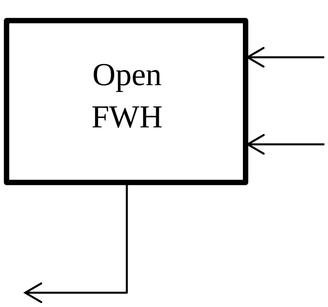

Figure 4: An Open Feed-water Heater

The steam goes into the turbine according to the boiler pressure (level 5) then it inflates isentropically with an intermediate pressure (level 6) is said to be an ideal regenerative

Rankine cycle. At this stage, some of the steam extracted and goes into the feedwater heater, which the remaining steam goes to the expansion process isentropically into the condenser pressure (level 7). This steam comes out of the condenser at a condenser pressure as a saturated liquid (level 1). The feedwater also known as condensed water, then goes into the isentropic pump where it is compressed through feedwater heater pressure (level 2) then it goes to the feedwater heater. Then the condensed water mixes with the turbine extracted steam. The proportion of the extracted steam is the one the heater throws the mixture out as the saturated liquid at heater pressure (level 3). At this stage, the second pump increases the water pressure equivalent to the boiler pressure (level 4). The completion of the cycle is done when water in the boiler heated at the turbine inlet (level 5). The explained process of steam power plants is convenient for the activities where the units are expressed in per unit of mass, and the steam is flowing in the boiler. The process explanation is that when 1 kg of steam leaves the boiler, y kg of the steam partially expands in the turbine which is then extracted at level 6.

The remaining *(1-y) kg* steam then goes to the condenser and completely expands. Hence, the different components have different mass flow rates. For example, if the rate of mass flow in the boiler is *n*, then it is (1-y)*n* in the condenser. The related T-S diagram is shown in the next phase.

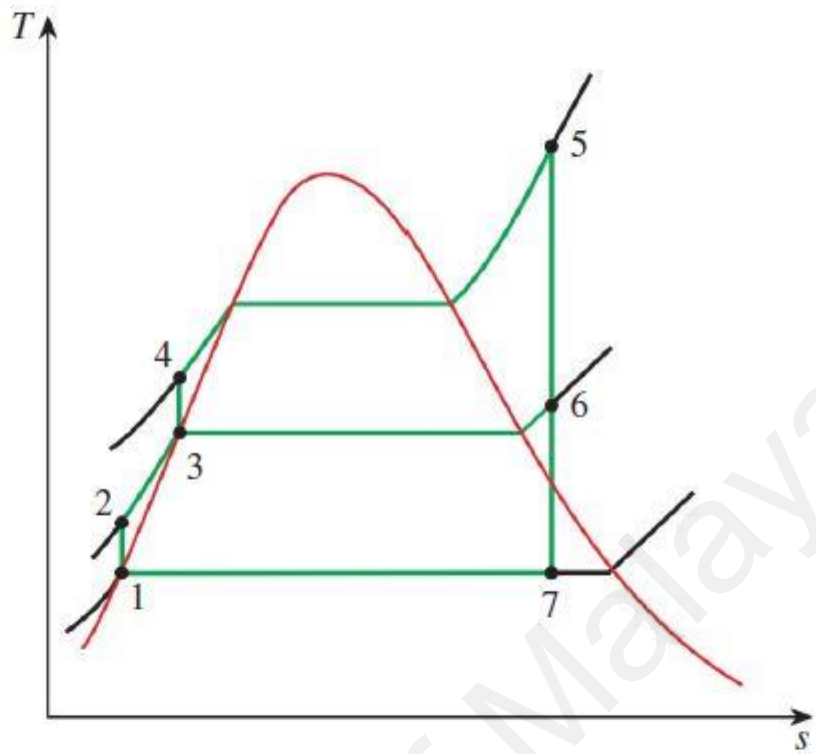

Figure 5 The Ideal Regenerative Rankine Cycle with An Open Feed-water Heater

3.3.5 Closed Feedwater Heater (CFWH)

Closed feedwater heater (CFWH) resembles with the open feedwater heater (OFWH), while the difference is both the inputs do not mix with each other and after exiting the pressure is adjusted in the closed feedwater heater; Figure 6 below shows the CFWH process:

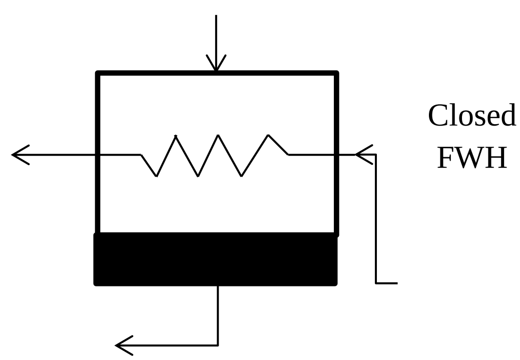

Figure 6 Closed Feedwater Heater

3.4 Increasing the Efficiency of Rankine Cycle

There are different ways adopted to increase the efficiency of Rankine cycle. Three ways are discussed as follows.

3.4.1 Decreasing the Condenser Pressure

The condenser holds steams in it as a saturated mixture at the saturation temperature as compared to the condensers inside temperature. Thus the temperature of the steam is automatically lowered condenser by decreasing the operating pressure, therefore the temperature at which heat is rejected. The effect of a decrease in the condensers pressure for increasing the efficiency of the Rankine cycle is explained in the T-S diagram below.

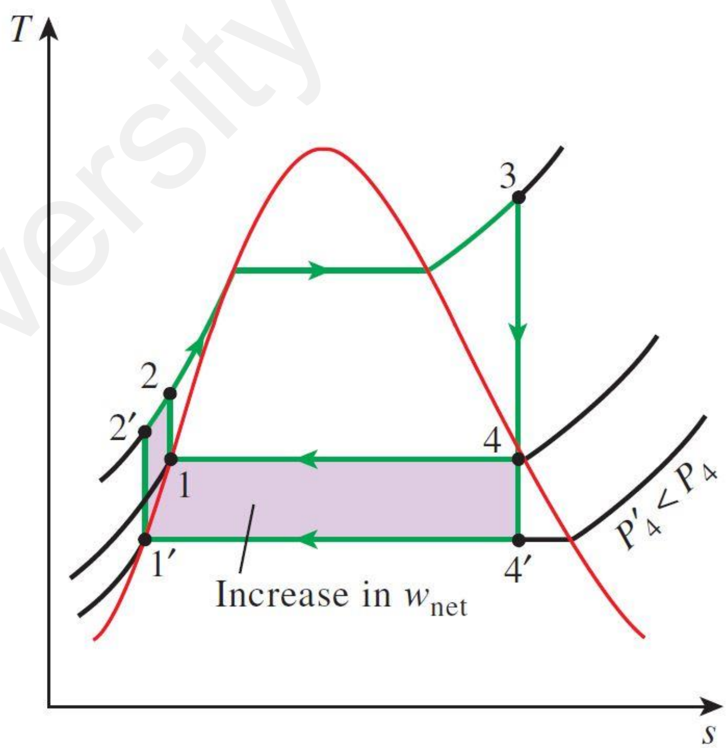

Figure 7 Decreasing the Condenser Pressure

The turbine inlet is maintained at the same level for the comparison purpose. In figure 7, the colored area explains the rise in work output which is obtained by decreasing the pressure of condenser from P_4 to P'_4. The requirements for heat input also increases (area under 2-2 curve explains), yet the increase is minimal. Therefore the thermal efficiency of the system is increased by lowering the overall effect of condenser pressure.

The steam condenser power plant normally works below the atmospheric pressure which makes it take advantage of maximum efficiency at lower pressure. As the vapor power cycle works under the closed loop, therefore, it does not have any vital problem. But the lower limit of condenser pressure is normally used here. Generally, it is not lesser than the corresponding saturation pressure as compared to the temperature of the cooling medium. For example, if the condenser is cooled by at 15°C by using the nearby river. To obtain the heat transfer effectively, it allows a difference in temperature of 10°C. Therefore the condenser's steam temperature should be more than 25°C; hence the pressure condenser should be more than 3.2 kPa, which is the pressure at saturation with 25°C.

There are no side effects of decreasing the condenser pressure; yet, there could be a possibility of air leakage in the condenser. More importantly, the moisture proportion in the steam increases in the final stages of the turbine. The existence of larger contents of moisture is adverse for the turbines as it does not only erode the turbine blades but also decreases the turbine efficiency. Providentially, the problem of inefficiency and erosion could be eradicated by the use of following.

3.4.2 Superheating the Steam to High Temperatures

The process of superheating the steam at high temperature leads to the increase in the average temperature of transferring heat to steam without the increase in boiler pressure. The T-S figure below explains the way by which the performance of vapor power cycle is affected by the super heating process.

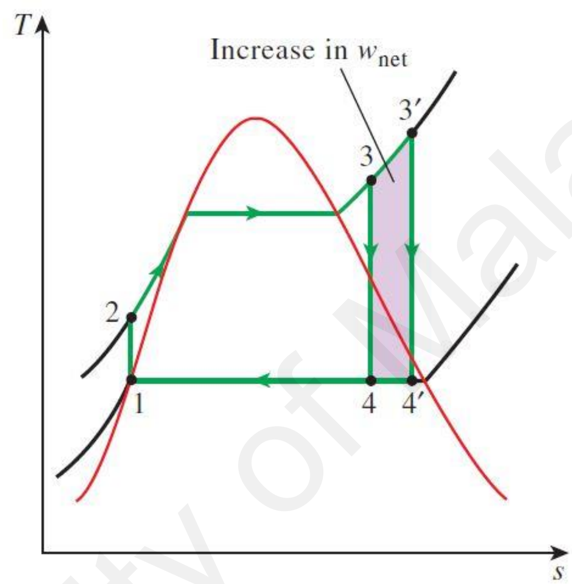

Figure 8 Superheating process

The increase in the output work is explained by the colored section of the diagram. The increase in the heat input is explained by the total area under process curve 3-3. Therefore, both heat input and output work increase due to the steam superheating at a higher temperature. Overall the thermal efficiency is increased while the average temperature increases when the heat is added. Another effect of super heating steam by giving high temperature; the moister elements are decreased at the turbine exit; the explanation is provided in the diagram T-S. By the metallurgical consideration, the superheated temperature of the steam is limited. Currently, the maximum allowed steam temperature for the turbine inlet is 620°C. Any increment in this temperature value could be because of improvement in the current material or finding another one which can work at a higher temperature. Ceramics are very promising in this regard.

3.4.2 Increasing the Boiler Pressure

The average temperature increase during the heat-addition process will increase the boiler's operating pressure; this will inevitably increase the boiling temperature. This will raise the average heat transferring temperature which will lead to the increase in thermal efficiency of the cycle. The performance of vapor power cycle would be noticed by the increase in the boiler pressure; this will lead to the shift in the cycle in the left direction, moreover, at the turbine exit, the moisture elements would be increased. This side effect could be corrected by the process of steam reheating; the next step will highlight this.

With respect to time, there is an increase in the boiler's operating pressure, there was the pressure of 2.7MPa (400 psia) in the year 1922 while now a days this noticed pressure is 30MPa (4500psia). This lead to generate enough steam which produces energy output of 1000MW or higher in the bigger power plants.

Nowadays number of advanced steam power plants work at supercritical pressure (P 22.06 MPa). The thermal efficiency of these power plants is 34% of nuclear plants and 40% of fossil fuel plants.

In the United States, there are more than 150 supercritical pressure steam power plants operating. The nuclear power plants are less efficient than this because of their lower maximum temperature which is controlled for the safety reasons.

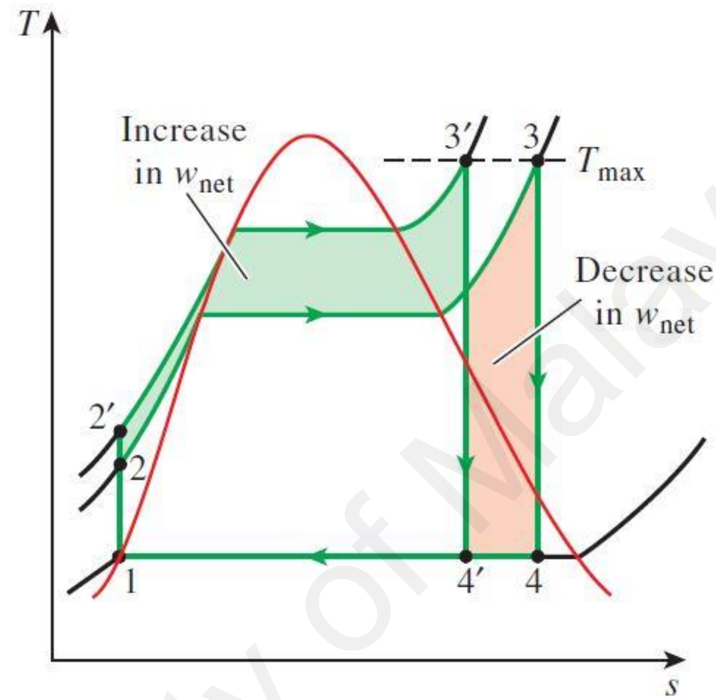

Figure 9 Increasing the Boiler Pressure

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the study was done on Kish power plant units and component property to calculate input and output of each unit diagram, and according to this information we suggest several ways to improve efficiency and use one to see how it will improve efficiency. Kish power plant which is located on the north side of Kish Island is the only Kish power plant with a production capacity of 275 MW and included nine gas units. According to the power plant information sheet, ninth and eighth units have 37.5 MW production capacities; Actual output power of this power plant is 205 MW. Kish power plant fuel is natural gas, which provided from Siri Island.

4.2 Kish Power Plant Units

Every component is working based on a closed Rankine cycle and consists of 7 Turbines and 2 boilers and two pumps for increasing Pressure and Primary temperature of make up water. For getting better efficiency feedwater heater used between two pumps input and output which increasing water temperature with exhausted steam from turbine component. In production cycle, only one boiler and two turbines are working, and output of each turbine is connected to a control duct which has two valves and every time closes one of the outputs. As said before, two turbines working in the cycle but for turbine exhaust turbine output only one output is included. Another component is generator with 25 MW power output. After transferring output work to generator mechanical work converts to electrical power as output power.

The practical Kish Power plant Diagram is shown below which includes 7 states.

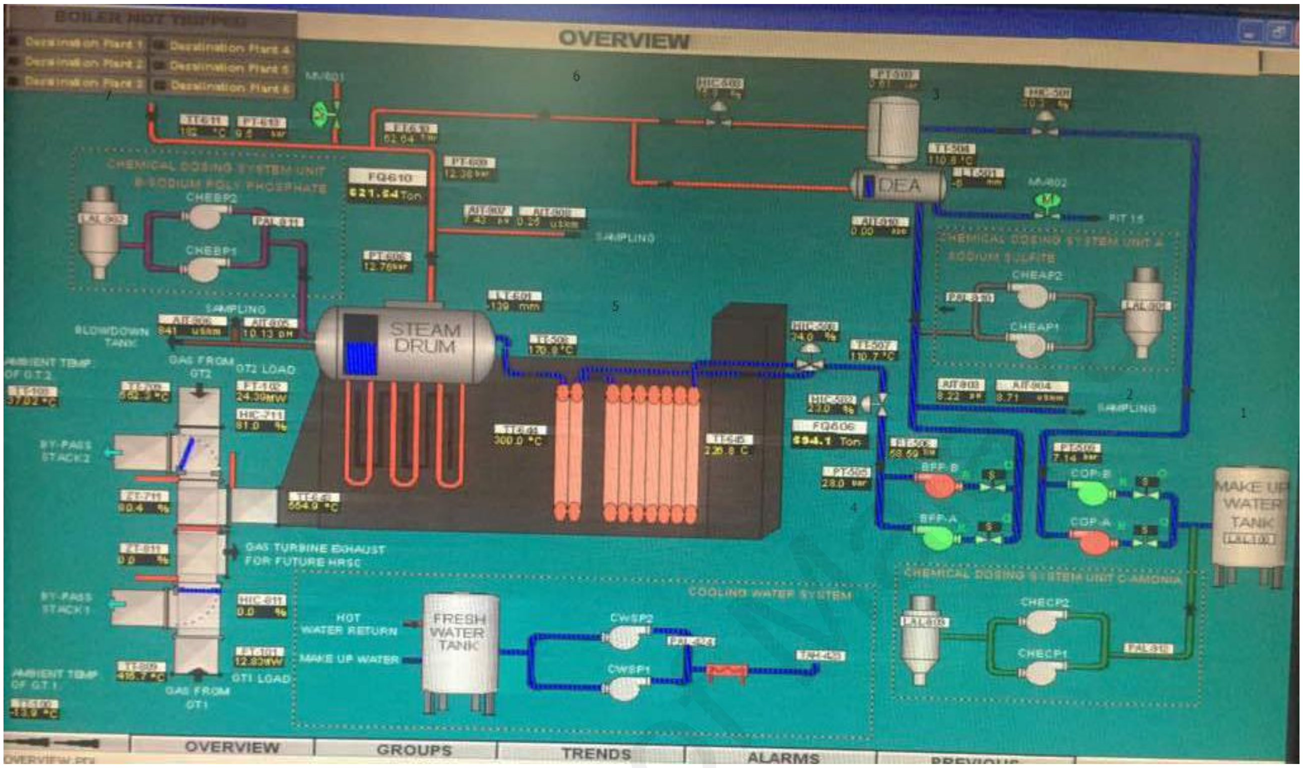

Figure 10 Kish Power Plant Diagram

At sate 1 condensed water stored under the name of make up water with 7.14_{bar} pressure and actually is compressed liquid (very close to saturated) , after that make up water pumped to the feed water heater with lina e pressure of 9.5_{bar} approximately compression will be consider isentropic with no heat loss, at state 3 after mixing with turbine steam mass fraction, It will pumped to the Boiler with line pressure of 28bar ,Boiling is occurred at constant pressure, at state 5 after boiling the temperature rise to the 600°C at turbine input, after entering the turbine some work will be done and the superheated water exit with lower temperature and pressure ,at state 6 some mass fraction of turbine input will be used as open feed water heater input to mix with condensed water. At state 7 lower pressure water condensed at the condenser and the output stored as Make up water. Kish power plant used desalination process as condensing.

4.2.1 Rankine cycle component Property Analyses

As discussed, Kish Power Plant closed cycle have seven states. To analyze each state for calculating efficiency of cycle, states are considered separately on the cycle schematic diagram as shown below:

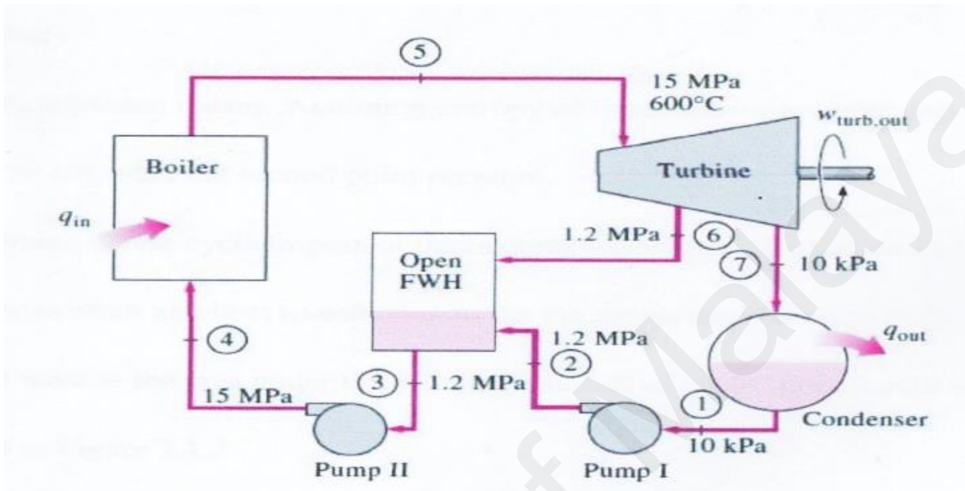

Figure 11 Kish Power Plant Schematic

Step one: First pump

From property table of water based on input pressure, finding enthalpy calculates work, this process will be considered as an isentropic process and entropy to output pressure of this step will be calculated form first point pressure and isentropic assumption. Isentropic approach means, assuming entropy of input and output of pump is equal in order to calculate the second point pressure. For analyzing whole cycle important parameters which was effective on Kish power plant as shown in efficiency as work and heat transferring to the cycle, based on close cycle T-S diagram. Cycle output work is the area under the T-S curve and all of cycle states, could be determined.

As T-S curve shown, pressure of each state and what kind of liquid is provided, could be determined at cycle states. For example after heating at the Boiler to get expected temperature, at the turbine input (state 5) what provided is superheated water.

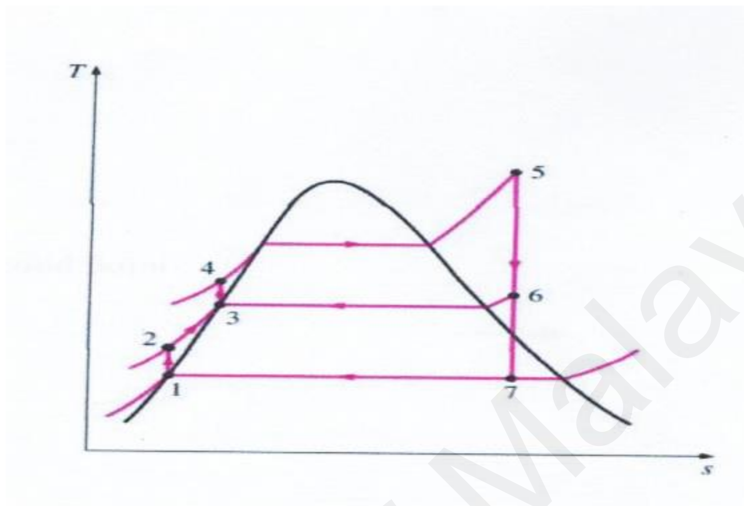

Figure 12 Pressure at Each State

As a matter of fact in actual cycle, water is compressed liquid in point 1 and it is not saturated completely but otherwise if it is so close to saturated liquid, then it will be approximately considered as saturated liquid as shown below:

State 1 (based on T-S curve):

At first point:

$P_{1(L)} = 7.14^{bar} = 721.14^{Kpa}$

Saturated liquid

Assuming the process is Isentropic then: $S_1 = S_2$

At second point:

$P_{2(M)} = 12.38^{bar} = 1250.38^{Kpa}$

$W_{pump_1} = \ v(p_2 - p_1)$

$W_{pump_1} = 0.001108(1250.38 - 721.14) = 0.586^{\frac{KJ}{KG}}$

$W + Q = h_2 - h_1$

$W_{pump} + Q = h_2 - h_1 \ \rightarrow Q = 0$

Assuming no heat loss on pumps:

$W_{pump_1} = h_2 - h_1$

$h_2 = W_{pump_1} + h_1 \rightarrow h_2 = 0.586 + 699.2 = 699.78^{\frac{KJ}{KG}}$,

After first pump we have Feedwater heater on cycle, for these analyses we assume the water on our middle pressure line is on saturated point, as discussed in state 1. For calculating work of second pump we need enthalpy and specific volume of state 3. At state 3, a mass fraction of turbine used to mixing with condensed water to increase condensed water temperature before entering the Boiler.

Step Two:

At state 3:

$P_{3(M)} = 1250.38^{Kpa}$

Saturated liquid

At state 4: On high pressure line

Assuming the process is Isentropic: $S_3 = S_4$

$P_{4(H)} = 28^{bar} = 2828^{Kpa}$

For calculating the second pump work:

$W_{pump_2} = v(p_4 - p_3)$

$W_{pump_2} = 0.001141(2828 - 1250.38) = 1.8^{\frac{KJ}{KG}}$

$W_{pump_2} = h_4 - h_3, h_4 = W_{pump_2} + h_3$

$h_4 = 1.8 + 804.46 = 808.26^{\frac{KJ}{KG}}$

After calculating work of both pumps then in the next state we have a Boiler which its output temperature is T = 552.3°C after heating water we have supper heated water on the state 5 ,on this step we have to analyze the turbine as a next cycle component. After entering superheated water, turbine uses energy of the superheated water to produce work. The output of the turbine is water with lower temperature and pressure to the condenser and excessive energy is waste as a turbine exhaust as a feedback to the Feedwater heater Component to help to warm up inlet water.

Step Three:

At state 5:

Again we assume from state 5 to 6 we have isentropic process: $S_5 = S_6$

$$P_{5(M)} = 2868^{Kpa}$$

At state 6: Turbine exhaust

$$P_{6(M)} = 1250.38^{Kpa}$$

At state 7: Turbine output at low pressure line)

This state is input of condenser for cooling the output water or after condensing water we have make up water to use it again. At Kish Island Power Plant we use Purifying water system and desalination method.

$P_{7(L)} = 721.14^{Kpa}$

Assuming Isentropic:

$S_7 = S_5$

For calculating the enthalpy of state 7, cause ⟶ $S_7 > \ S_g$ then still water is superheated

The energy analysis of open Feedwater heaters is identical to the energy analysis of mixing chambers. The Feedwater heaters are generally well insulated *(Q =0),* and they do not involve any work interactions *(W =0).* By neglecting the kinetic and potential energies of the streams, the energy balance reduces for a Feedwater heater to:

$\dot{E}_{in} = \dot{E}_{out} \, , \sum_{in} \dot{m}h = \sum_{out} \dot{m}h$

$yh_6 + (1 - y)h_2 = h_3$

Where *y* is the fraction of steam extracted from the turbine (*y* = $\frac{\dot{m}_6}{\dot{m}_5}$, solving for *y* and substituting the enthalpy values, we find:

$$y = \frac{h_3 - h_2}{h_6 - h_2} = \frac{806.46 - 699.78}{3257.28 - 699.78} = 0.041$$

$$q_{in} = h_3 - h_4 = 3570 - 808.26 = 2761.74 \frac{KJ}{KG}$$

$$q_{out} = (1 - y)(h_7 - h_1) = (1 - 0.04)(3120.67 - 699.2) = 2300.1 \frac{KJ}{KG}$$

Then the last part is efficiency calculation:

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{2300.1}{2761.74} = 0.164$$

Below is also the simulation of the above schematics done using Engineering Equation Software (EES). The equations were written as codes to simulate the principles of Rankine cycle. These principles are later used within simulations of suggested methods for improving the efficiency.

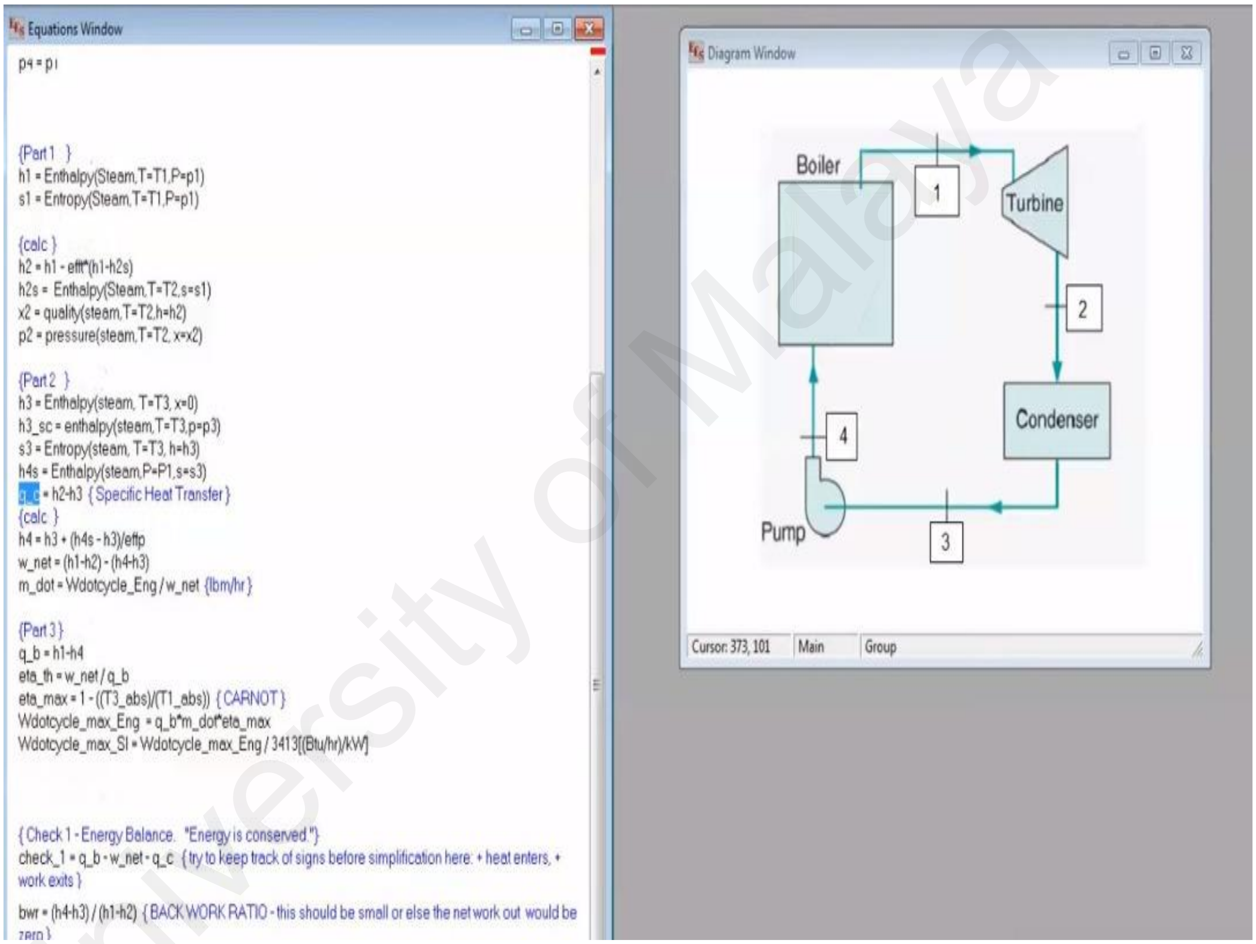

Figure 13 Simple Rankine Cycle Simulation of Kish Power Plant

4.2.1.1 Discussion

As shown above after calculation, heat loss is too much and for getting higher efficiency we should use a method to make this smaller and around half of input heat. For getting better result on efficiency, a closed feedwater heater can be added after exhausted steam from turbine. The difference of closed feedwater heater and open feedwater heater is extracted steam which has exit temperature and pressure without mixing but in real power plant a few temperature drop will happen after closed feedwater heater. The output is saturated liquid and increasing pressure could be performed separately for each of condensed water and exhausted steam after closed feedwater heater.

In this process the energy loss is lower, beside the increasing in pressure for output could be done up to high pressure line for make up water and excessive work does not need to be done all pressure is high pressure after pumping which is the effect of closed feedwater heater as pressure was not changed.

4.2.2 Analyzing first cycle improvement method

A new cycle component as closed feedwater heater added after turbine, as shown below, for increasing boiler pressure. Increasing condensed water pressure to maximum, at the same temperature with turbine output after entering close feed water heater.

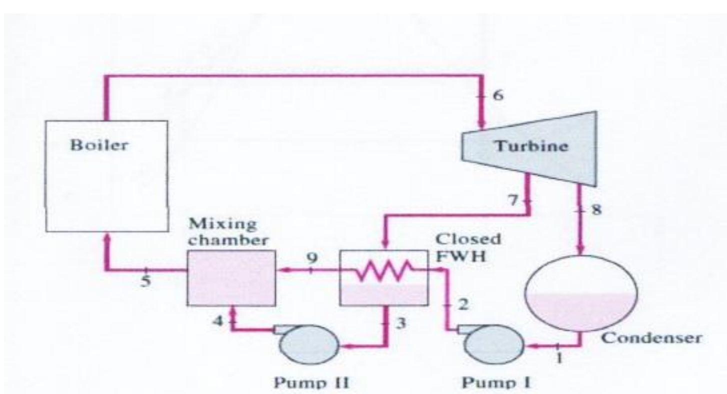

Figure 14 First Cycle Improvement (CFWH)

New cycle includes 9 states based on. It is clear 2 new states will be added to previous cycle, as mass fraction of turbine exhausted steam entered the closed feedwater heater with condensed water, without any mixing happened.

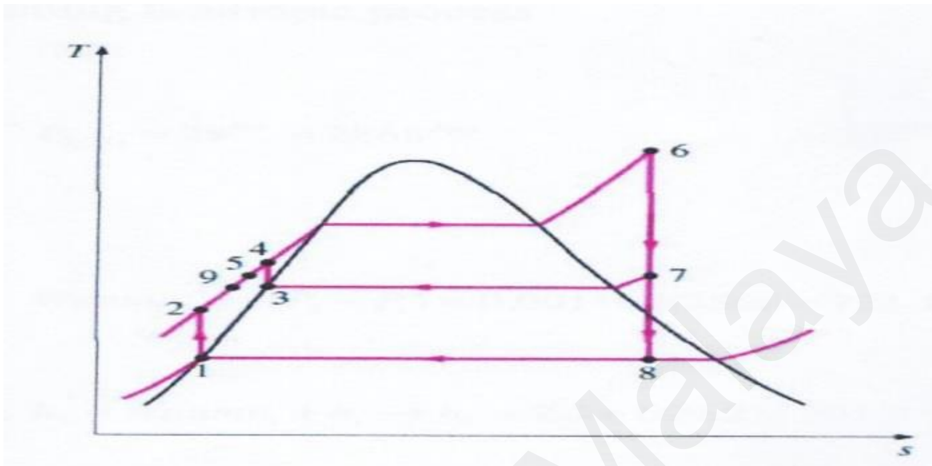

Figure 15 T-S Diagram First Cycle Improvement (CFWH)

At state 1:

$P_{1(L)} = 7.14^{bar} = 721.14^{Kpa}$

At state 2:

Assuming Isentropic process: $S_6 = S_7$

$P_{2(H)} = 28^{bar} = 2686^{Kpa}$, $(S_1 = S_2)$

$W_{pump_1} = v(p_2 - p_1) = 0.001108(2868 - 721.14) = 2.3^{Kpa}$

$h_2 = W_{pump_1} + h_1, h_2 = 2.3 + 699.2 = 701.5^{\frac{KJ}{KG}}$

At state 3:

$P_{3(M)} = 1250.38^{Kpa}$

Saturated liquid

At state 4:

Assuming Isentropic process: $S_3 = S_4$

$P_{4(H)} = 28^{bar} = 2686^{Kpa}$

$W_{pump_2} = v(p_4 - p_3) = 0.001141(2868 - 1250.38) = 1.8^{Kpa}$

$h_4 = W_{pump_2} + h_3, h_4 = 1.8 + 806.46 = 808.26^{\frac{KJ}{KG}}$

At state 5:

For calculating h_5, h_9 and y should be calculated. Consider the process from State 7 to calculate mass fraction (y).

At state 7:

$P_{6(H)} = 2686^{Kpa}$

Assuming the process is Isentropic for exhausted steam at state 7: $S_6 = S_7$

$P_{7(M)} = 1250.38^{Kpa}$

At state 8:

As considered Isentropic process again: $S_6 = S_8$

$P_{8(L)} = 721.14^{Kpa}$

With comparing $S_8 > S_g$ then the result is superheated:

At state 9:

Compressed water is at T_3 = 189.88°C because make up water after entering close Feedwater heate, its temperature raised to be equal to exhausted steam with a few dropping.

$P_{9(H)} = 2686^{Kpa}, h_9 = 805.09^{\frac{KJ}{KG}}$

Then for calculation of mass fraction, writing energy-mass balance for closed Feedwater heater:

$$\dot{E}_{in} = \dot{E}_{out}, \sum_{in} \dot{m}h = \sum_{out} \dot{m}h$$

$$yh_7 + (1-y)h_2 = yh_3 + (1-y)h_9$$

$$y = \frac{h_9 - h_2}{(h_1 - h_2) + (h_9 - h_3)} = \frac{805.09 - 701.5}{(3257.28 - 701.5) + (805.09 - 806.46)} = 0.0405$$

At state 5:

Writing energy balance for open Feedwater heater:

$$y = \frac{h_5 - h_9}{h_4 - h_9}$$

$$h_5 = y(h_4 - h_9) + h_9 = 805.21^{\frac{KJ}{KG}}$$

For efficiency calculation, we need input heat at Boiler and heat loss at condenser which will be calculated as below:

$$q_{in} = h_6 - h_5 = 3570 - 805.21 = 2764.79^{\frac{KJ}{KG}}$$

$$q_{out} = (1-y)(h_8 - h_1) = (1 - 0.0405)(3120.67 - 699.2) = 2300.1^{\frac{KJ}{KG}}$$

Then last part is efficiency calculation:

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{2300.1}{2764.79} = 0.168$$

Below is the simulation of the above schematics done using Thermoflow software. Codes written for principles of Rankine cycle in the previous simulation were used in Thermoflow in order to have accurate results.

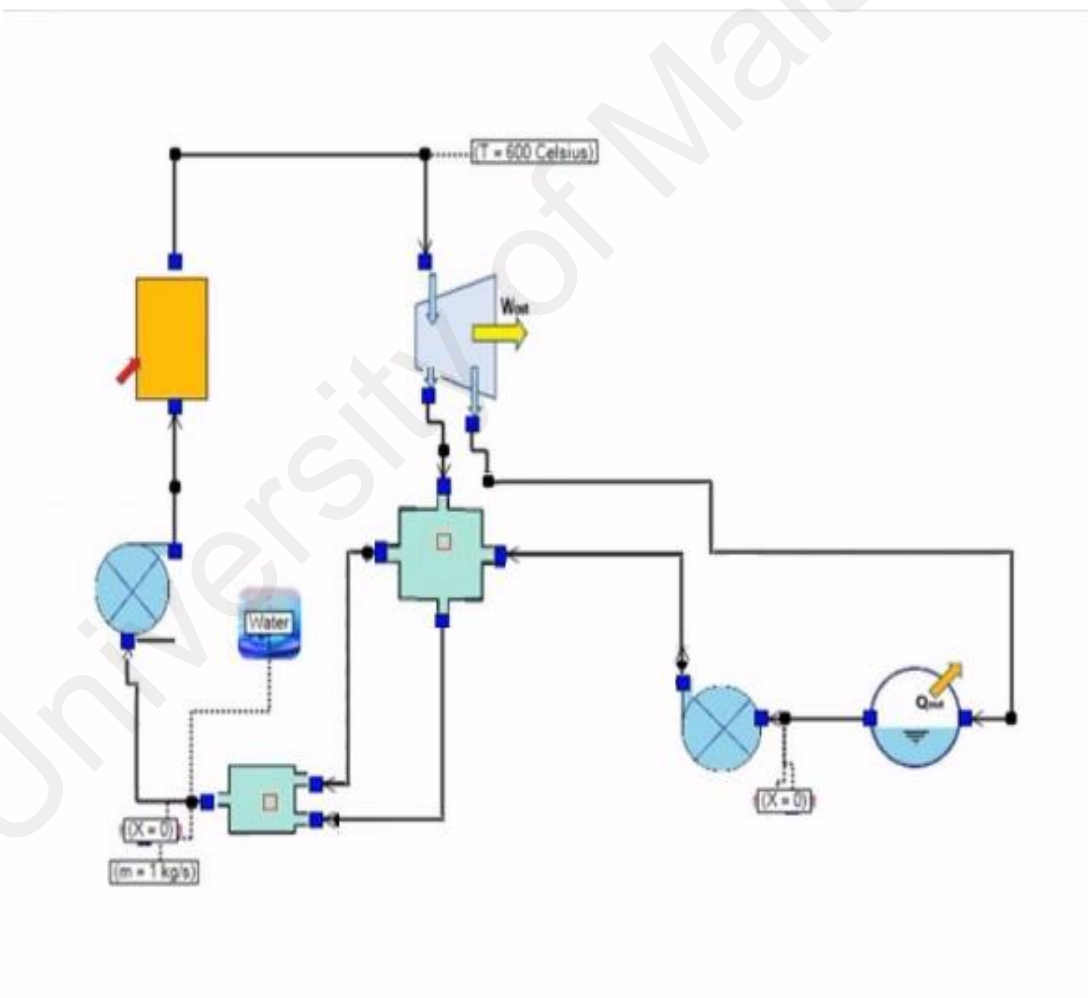

Figure 16 Simulation of the System After Adding Closed Feedwater Heater

4.2.2.1 Discussion

This result shows that closed feedwater heater and mixing chamber made efficiency better, because after mixing chamber, enthalpy of mixture is lower than $q_{in}$is larger. On the other hand, with constant heat loss efficiency could be greater. The other thing could be considered is mass friction, with increasing this parameter efficiency will be increased as heat loss decreases.

4.2.3 Cycle Improvement with Re-heater

For increasing efficiency another suggestion, is adding a Re-heater to the cycle as shown for comparing the effect of this method, calculate efficiency to see how it will improve.

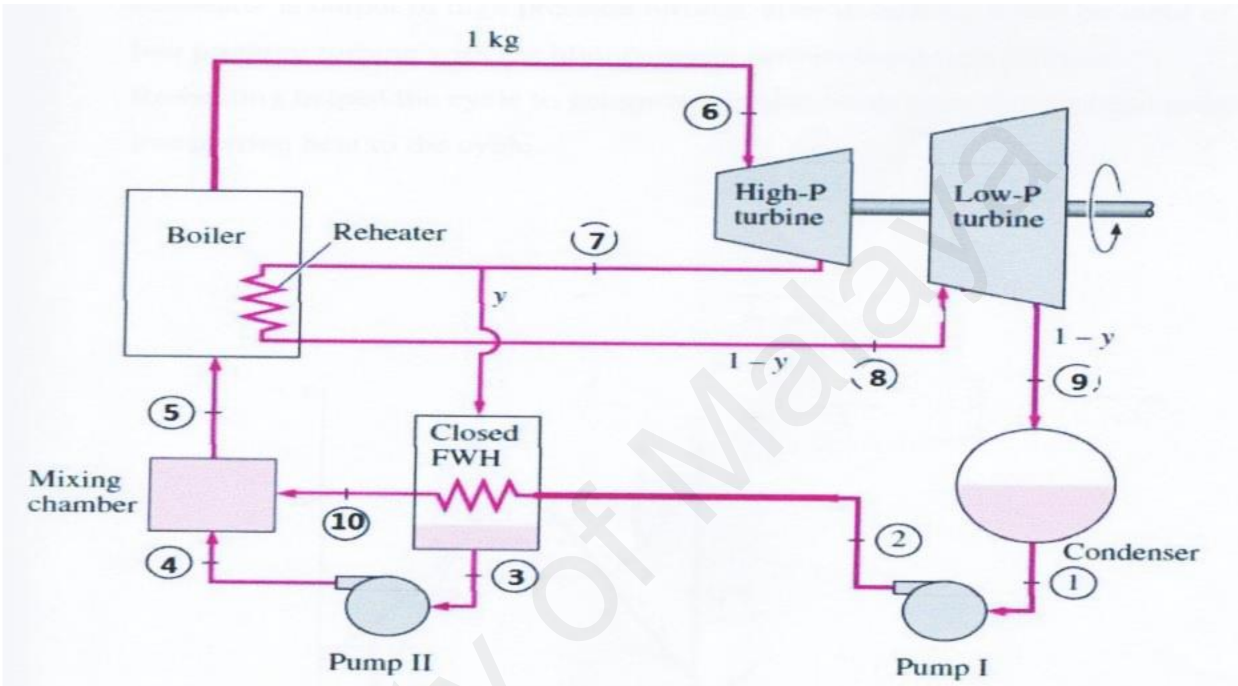

Figure 17 Cycle Improvement with Re-heater

In this cycle additional state will be added to previous analyses as shown in. First one is a Re-heater from state 7-8. Two turbines of which one is low pressure and the other is high pressure. Input of Re-heater is output of high pressure turbine and after re-heating it will be input of low pressure turbine with the high pressure turbine input temperature. Re-heating helped the cycle to get greater output work from turbines and more transferring of heat to the cycle.

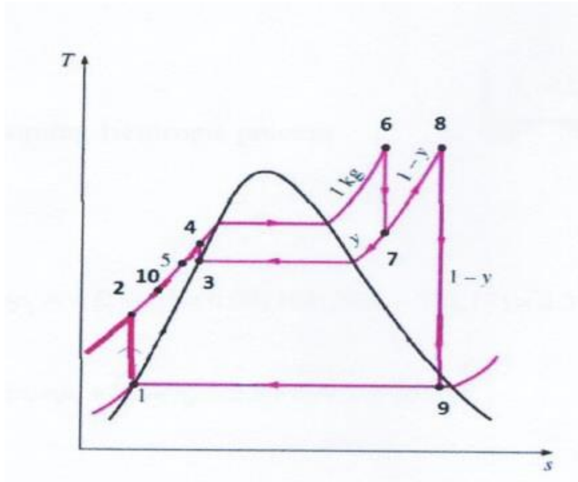

Figure 18 T-S Diagram Cycle Improvement with Re-heater

Cycle Analyzing

At state 1:

$P_{1(L)} = 7.14^{bar} = 721.14^{Kpa}$

At state 2:

Assuming Isentropic process: $S_1 = S_2$

$W_{pump_1} = v(p_2 - p_1) = 0.001108(2868 - 721.14) = 2.3^{Kpa}$

$h_2 = W_{pump_1} + h_1, h_2 = 2.3 + 699.2 = 701.5^{\frac{KJ}{KG}}$

At state 3:

$P_{3(M)} = 1250.38^{Kpa}$

Saturated liquid

At state 4:

Assuming isentropic process: $S_3 = S_4$

$P_{4(H)} = 28^{bar} = 2686^{Kpa}$

$W_{pump_2} = v(p_4 - p_3) = 0.001141(2868 - 1250.38) = 1.8^{Kpa}$

$h_4 = W_{pump_2} + h_3, h_4 = 1.8 + 806.46 = 808.26^{\frac{KJ}{KG}}$

At state 5:

For calculation of h_5, h_9 and *y* should be calculated.

Consider the process from state 7 to calculate mass fraction (*y*).

At state 7:

$P_{6(H)} = 2686^{Kpa}$

Assuming the process is Isentropic for exhausted steam at state 7: $S_6 = S_7$

$P_{7(M)} = 1250.38^{Kpa}$

Up to here cycle was completely like previous one, after state 7 output of high pressure turbine entered Re-heater (state 8), it will be Re-heated to T_6 = 552.3 C , at state 9 it will condensed.

At state 8 exhausted steam of low pressure turbine is going to close Feedwater heater.

At state 8:

$P_{8(M)} = 1250.38^{Kpa}$

Assuming process is Isentropic: $S_8 = S_9$

At state 9:

$P_{9(L)} = 721.14^{Kpa}$

With comparing $S_9 > S_g$ then water is superheated:

Then for calculation of mass fraction, writing energy-mass balance for closed Feedwater heater:

$$\dot{E}_{in} = \dot{E}_{out}\ , \sum_{in} \dot{m}h = \sum_{out} \dot{m}h$$

$$yh_7 + (1-y)h_2 = yh_3 + (1-y)h_9$$

$$y = \frac{h_{10} - h_2}{(h_7 - h_2) + (h_{10} - h_3)} = \frac{805.09 - 701.5}{(3257.28 - 701.5) + (805.09 - 806.46)} = 0.0405$$

At state 5:

Writing energy balance for open Feedwater heater:

$$y = \frac{h_5 - h_9}{h_4 - h_9}$$

$$h_5 = y(h_4 - h_9) + h_9 = 805.21^{\frac{KJ}{KG}}$$

For calculating efficiency in this cycle, water takes heat twice of which first was at Boiler and second one was Re-heat, then according to below efficiency will be calculated:

$$q_{in} = (1-y)(h_8 - h_7) + (h_6 - h_5) = 3079$$

$$q_{out} = (1-y)(h_9 - h_1) = 2480.22^{\frac{KJ}{KG}}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{2480.22}{3079} = 0.19$$

Below is also the simulation of the above schematics done using Thermoflow software. Codes written for principles of Rankine cycle in the previous simulation were used in Thermoflow in order to have accurate results.

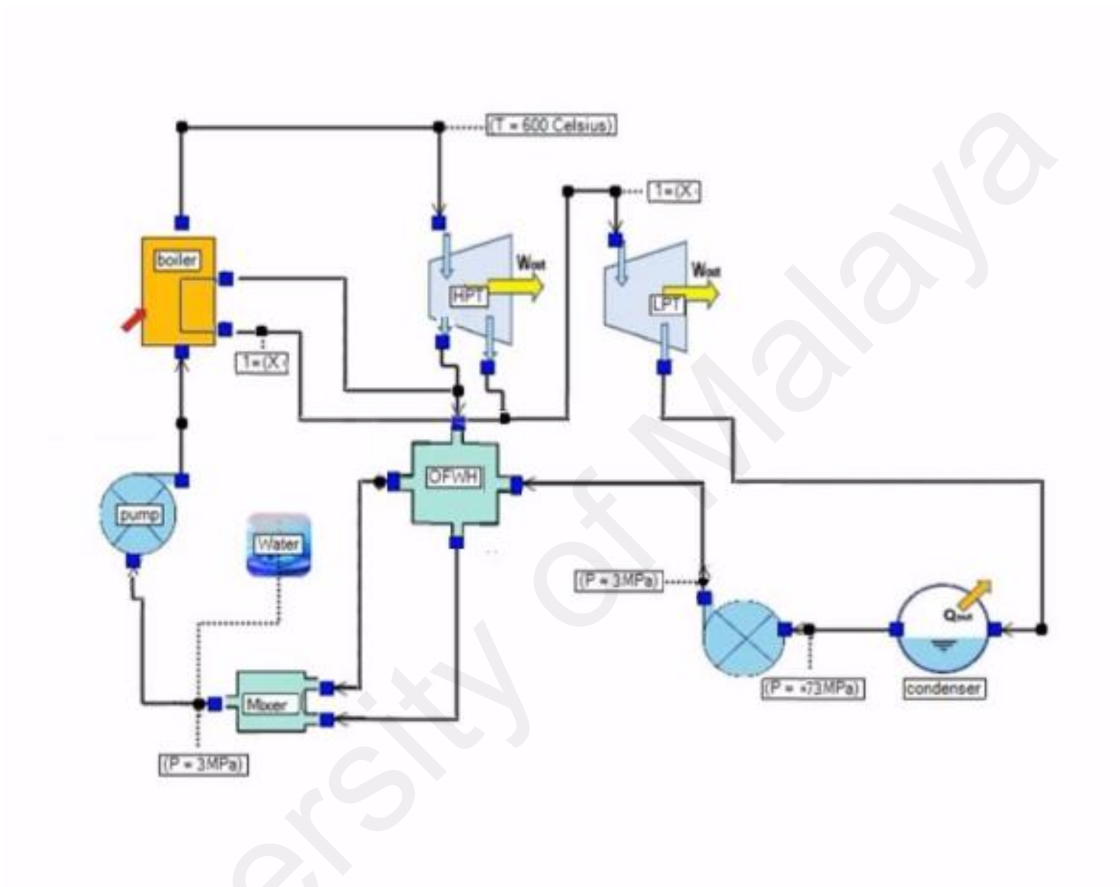

Figure 19 Simulation of the System After Adding Re-heater

4.2.3.1 Discussion

As the result shows efficiency is increased because by re-heating, q_{in} will be greater and $W_{net}$is increased too, but $W_{net}$with respect to q_{in} had smaller increase than ratio of formula will be smaller than efficiency as a result growth.

By reheating after high turbine steam will be at input temperature of high pressure turbine as an input for low pressure turbine and with this issue, more output work can be produced.

CHAPTER 5: CONCLUSION

5.1 Introduction

In this chapter, everything that has been done and objectives which have achieved will be briefly discussed. Additionally, some alternative methods are suggested for future work in order to improve the efficiency of the power plant and minimizing energy losses.

5.2 Conclusion

This research was developed based on the use of Rankine cycle in gas power plants. This study proposes that enhancing Rankine cycle modeling can help improve the efficiency.

There are three ways suggested in this research to enhance the efficiency of Rankine Cycle:

1. Decreasing the condenser pressure
2. Superheating the system to high temperatures
3. Increasing the boiler pressure

In particular, the investigation was conducted on Kish gas-steam power plant as the current system quite suffers from energy losses due to utilization of aged equipment. Since there is no access to the latest technology, study focuses on ways and methods which can achieve the objectives by using the available tools and technology. As a result, analysis and calculations were performed by using the real efficiency data of this power plant and according to the data collected, two methods were suggested:

1. Using closed feedwater heater
2. Adding a re-heater

According to the result collected from the calculations, it was clear that the using closed feedwater heater has minor effect and the efficiency was reduced by 4%. However, adding a re-heater drew results which promise improvement on the efficiency as the calculations show it to be more effective on the power plant and efficiency was increased by 19%.

This impressing result in efficiency is due to using two (high and low pressure) turbines. The high pressure turbine isolates and transfers the extra heat to boiler as well as the closed feedwater heater. As a result, there will be less heat losses and having the preserved heat to increase the temperature in boiler and closed feedwater heater which leads to less energy input. This was, there will be slightly more output work but a significant less input energy as well as less heat loss.

However, there will still be energy losses and adapting modern technologies can result in much better efficiency and Kish power plant needs to start implementing the latest technologies as soon as possible. Additionally, other energy sources such as solar should be considered as they can avoid using fossil fuels and they can be very cost effective as well as environmentally friendly.

5.3 Recommendation for Future Project

Solar thermal power plant technologies have become quite significant for providing a major share of the clean and renewable energy required in the future. Solar thermal power stations are among the most cost-effective renewable power technologies as they promise to become competitive with fossil fuel plants within the next decade.

In this method, concentrated sunlight is integrated to the feedwater heater before entering into the boiler of a steam power plant. To achieve better performance, sun tracking mirrors may be introduced to follow the path of the sun.

BIBLIOGRAPHY

Bayrak, Z. U., Bayrak, G., Ozdemir, M. T., Gencoglu, M. T., & Cebeci, M. (2016). A low-cost power management system design for residential hydrogen & solar energy based power plants. *International Journal of Hydrogen Energy, 41*(29), 12569-12581. doi: 10.1016/j.ijhydene.2016.01.093

Beér, J. M. (2007). High efficiency electric power generation: The environmental role. *Progress in Energy and Combustion Science, 33*(2), 107-134. doi: 10.1016/j.pecs.2006.08.002

Bugge, J., Kjær, S., & Blum, R. (2006). High-efficiency coal-fired power plants development and perspectives. *Energy, 31*(10-11), 1437-1445. doi: 10.1016/j.energy.2005.05.025

Çengel, Y. A., & Boles, M. A. (2015). *Thermodynamics : an engineering approach* (8th ed.). the United States of America: McGraw-Hill Education.

Cocco, D., & Serra, F. (2015). Performance comparison of two-tank direct and thermocline thermal energy storage systems for 1 MWe class concentrating solar power plants. *Energy, 81*, 526-536. doi: 10.1016/j.energy.2014.12.067

Descamps, C., Bouallou, C., & Kanniche, M. (2008). Efficiency of an Integrated Gasification Combined Cycle (IGCC) power plant including CO2 removal. *Energy*, *33*(6), 874-881. doi: 10.1016/j.energy.2007.07.013

Drescher, U., & Brüggemann, D. (2007). Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants. *Applied Thermal Engineering, 27*(1), 223-228. doi: 10.1016/j.applthermaleng.2006.04.024

Ehtiwesh, I. A. S., Coelho, M. C., & Sousa, A. C. M. (2016). Exergetic and environmental life cycle assessment analysis of concentrated solar power plants. *Renewable and Sustainable Energy Reviews, 56*, 145-155. doi: 10.1016/j.rser.2015.11.066

Farhad, S., Saffar-Avval, M., & Younessi-Sinaki, M. (2008). Efficient design of feedwater heaters network in steam power plants using pinch technology and exergy analysis. *International Journal of Energy Research, 32*(1), 1-11. doi: 10.1002/er.1319

Franco, A., & Casarosa, C. (2002). On some perspectives for increasing the efficiency of combined cycle power plants. *Applied Thermal Engineering, 22,* 1501-1518. doi: 10.1016/S1359-4311(02)00053-4

Gupta, M. K., & Kaushik, S. C. (2010). Exergy analysis and investigation for various feed water heaters of direct steam generation solar–thermal power plant. *Renewable Energy, 35*(6), 1228-1235. doi: 10.1016/j.renene.2009.09.007

Habib, M. A., & Zubair, S. M. (1992). Second-law-based thermodynamic analysis of regenerative-reheat Rankine-cycle power plants. *Energy, 17*(3), 295-301. doi: 10.1016/0360-5442(92)90057-7

Harvey, S. P., & Richter, H. J. (1997). Gas Turbine Cycles With Solid Oxide Fuel Cells—Part I Improved Gas Turbine Power Plant Efficiency by Use of Recycled Exhaust Gases and Fuel Cell Technology. *J. Energy Resour. Technol, 116*(4), 305-311. doi: 10.1115/1.2906458

Hoffmann, J. F., Fasquelle, T., Goetz, V., & Py, X. (2016). A thermocline thermal energy storage system with filler materials for concentrated solar power plants: Experimental data and numerical model sensitivity to different experimental tank scales. *Applied Thermal Engineering, 100,* 753-761. doi: 10.1016/j.applthermaleng.2016.01.110

Hübner, S., Eck, M., Stiller, C., & Seitz, M. (2016). Techno-economic heat transfer optimization of large scale latent heat energy storage systems in solar thermal power plants. *Applied Thermal Engineering, 98,* 483-491. doi: 10.1016/j.applthermaleng.2015.11.026

HUNG, T.-C. (2001). Waste heat recovery of organic Rankine cycle using dry fluids. *Energy Conversion and Management, 42,* 539-553.

HUNG, T. C., SHAI, T. Y., & WANG, S. K. (1997). A REVIEW OF ORGANIC RANKINE CYCLES (ORCs) FOR THE RECOVERY OF LOW-GRADE WASTE HEAT. *Energy, 22*(7), 661-667. doi: 10.1016/S0360-5442(96)00165-X

Ibrahim, T. K., Rahman, M. M., & Abdalla, A. N. (2011). Improvement of gas turbine performance based on inlet air cooling systems: A technical review. *Physical Sciences, 6*(4), 620-627. doi: 10.5897/ijps10.563

Invernizzi, C., Iora, P., & Silva, P. (2007). Bottoming micro-Rankine cycles for micro-gas turbines. *Applied Thermal Engineering, 27*(1), 100-110. doi: 10.1016/j.applthermaleng.2006.05.003

ISHIKAWA, M., TERAUCHI, M., KOMORI, T., & YASURAOKA, J. (2008). Development of High Efficiency Gas Turbine Combined Cycle Power Plant. *Technical Review, 45*(1).

Kalinda, A. I. (2009). Combined-Cycle System With Novel Bottoming Cycle. *Gas Turbines Power, 106*(4), 737-742. doi: 10.1115/1.3239632

KRIBUS, A., ZAIBEL, R., CAREY, D., SEGAL, A., & KARNI, J. (1998). A solar-driven combined cycle power plant. *Solar Energy, 62*(2), 121-129. doi: 10.1016/S0038-092X(97)00107-2

Larjola, J. (1995). Electricity from industrial waste heat using high-speed organic Rankine cycle (ORC). *Production Economics, 41*, 227-235. doi: 10.1016/0925-5273(94)00098-0

Liu, M., Steven Tay, N. H., Bell, S., Belusko, M., Jacob, R., Will, G., . . . Bruno, F. (2016). Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies. *Renewable and Sustainable Energy Reviews, 53*, 1411-1432. doi: 10.1016/j.rser.2015.09.026

Madhawa Hettiarachchi, H. D., Golubovic, M., Worek, W. M., & Ikegami, Y. (2007). Optimum design criteria for an Organic Rankine cycle using low-temperature geothermal heat sources. *Energy, 32*(9), 1698-1706. doi: 10.1016/j.energy.2007.01.005

Mao, Q. (2016). Recent developments in geometrical configurations of thermal energy storage for concentrating solar power plant. *Renewable and Sustainable Energy Reviews, 59*, 320-327. doi: 10.1016/j.rser.2015.12.355

Mortensen, J. H., Moelbak, T., Andersen, P., & Pedersen, T. S. (1998). Optimization of boiler control to improve the load-following capability of power-plant units. *Control Engineering Practice, 6*, 1531-1539. doi: 10.1016/S0967-0661(98)00114-2

Pilavachi, P. A. (2000). Power generation with gas turbine systems and combined heat and power. *Applied Thermal Engineering, 20*, 1421-1429. doi: 10.1016/S1359-4311(00)00016-8

Quoilin, S., Broek, M. V. D., Declaye, S., Dewallef, P., & Lemort, V. (2013). Techno-economic survey of Organic Rankine Cycle (ORC) systems. *Renewable and Sustainable Energy Reviews, 22*, 168-186. doi: 10.1016/j.rser.2013.01.028

Rosen, M., & Bulucea, C. A. (2009). Using Exergy to Understand and Improve the Efficiency of Electrical Power Technologies. *Entropy, 11*(4), 820-835. doi: 10.3390/e11040820

Schuster, A., Karellas, S., Kakaras, E., & Spliethoff, H. (2009). Energetic and economic investigation of Organic Rankine Cycle applications. *Applied Thermal Engineering, 29*(8-9), 1809-1817. doi: 10.1016/j.applthermaleng.2008.08.016

Shengjun, Z., Huaixin, W., & Tao, G. (2011). Performance comparison and parametric optimization of subcritical Organic Rankine Cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation. *Applied Energy, 88*(8), 2740-2754. doi: 10.1016/j.apenergy.2011.02.034

Sun, J., & Li, W. (2011). Operation optimization of an organic rankine cycle (ORC) heat recovery power plant. *Applied Thermal Engineering, 31*(11-12), 2032-2041. doi: 10.1016/j.applthermaleng.2011.03.012

Tan, Y., Douglas, M. A., & Thambimuthu, K. V. (2002). CO2 capture using oxygen enhanced combustion strategies for natural gas power plants. *Fuel, 81*, 1007-1016. doi: 10.1016/S0016-2361(02)00014-5

Tchanche, B. F., Lambrinos, G., Frangoudakis, A., & Papadakis, G. (2011). Low-grade heat conversion into power using organic Rankine cycles – A review of various applications. *Renewable and Sustainable Energy Reviews, 15*(8), 3963-3979. doi: 10.1016/j.rser.2011.07.024

Tchanche, B. F., Papadakis, G., Lambrinos, G., & Frangoudakis, A. (2009). Fluid selection for a low-temperature solar organic Rankine cycle. *Applied Thermal Engineering, 29*(11-12), 2468-2476. doi: 10.1016/j.applthermaleng.2008.12.025

Valdés, M., Durán, M. D., & Rovira, A. (2003). Thermoeconomic optimization of combined cycle gas turbine power plants using genetic algorithms. *Applied Thermal Engineering, 23*(17), 2169-2182. doi: 10.1016/s1359-4311(03)00203-5

Vignarooban, K., Xu, X., Arvay, A., Hsu, K., & Kannan, A. M. (2015). Heat transfer fluids for concentrating solar power systems – A review. *Applied Energy, 146*, 383-396. doi: 10.1016/j.apenergy.2015.01.125

Wang, D., Ling, X., Peng, H., Liu, L., & Tao, L. (2013). Efficiency and optimal performance evaluation of organic Rankine cycle for low grade waste heat power generation. *Energy, 50*, 343-352. doi: 10.1016/j.energy.2012.11.010

Wei, D., Lu, X., Lu, Z., & Gu, J. (2007). Performance analysis and optimization of organic Rankine cycle (ORC) for waste heat recovery. *Energy Conversion and Management, 48*(4), 1113-1119. doi: 10.1016/j.enconman.2006.10.020

Xu, B., Li, P., & Chan, C. (2015). Application of phase change materials for thermal energy storage in concentrated solar thermal power plants: A review to recent developments. *Applied Energy, 160*, 286-307. doi: 10.1016/j.apenergy.2015.09.016

Yamaguchi, H., Zhang, X. R., Fujima, K., Enomoto, M., & Sawada, N. (2006). Solar energy powered Rankine cycle using supercritical CO2. *Applied Thermal Engineering, 26*(17-18), 2345-2354. doi: 10.1016/j.applthermaleng.2006.02.029

APPENDIX A

Saturated water—Temperature table

		Specific volume, ft³/lbm		Internal energy, Btu/lbm			Enthalpy, Btu/lbm			Entropy, Btu/lbm·R		
Temp., T °F	Sat. press., P_{sat} psia	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
32.018	0.08871	0.01602	3299.9	0.000	1021.0	1021.0	0.000	1075.2	1075.2	0.00000	2.18672	2.1867
35	0.09998	0.01602	2945.7	3.004	1019.0	1022.0	3.004	1073.5	1076.5	0.00609	2.17011	2.1762
40	0.12173	0.01602	2443.6	8.032	1015.6	1023.7	8.032	1070.7	1078.7	0.01620	2.14271	2.1589
45	0.14756	0.01602	2035.8	13.05	1012.2	1025.3	13.05	1067.8	1080.9	0.02620	2.11587	2.1421
50	0.17812	0.01602	1703.1	18.07	1008.9	1026.9	18.07	1065.0	1083.1	0.03609	2.08956	2.1256
55	0.21413	0.01603	1430.4	23.07	1005.5	1028.6	23.07	1062.2	1085.3	0.04586	2.06377	2.1096
60	0.25638	0.01604	1206.1	28.08	1002.1	1030.2	28.08	1059.4	1087.4	0.05554	2.03847	2.0940
65	0.30578	0.01604	1020.8	33.08	998.76	1031.8	33.08	1056.5	1089.6	0.06511	2.01366	2.0788
70	0.36334	0.01605	867.18	38.08	995.39	1033.5	38.08	1053.7	1091.8	0.07459	1.98931	2.0639
75	0.43016	0.01606	739.27	43.07	992.02	1035.1	43.07	1050.9	1093.9	0.08398	1.96541	2.0494
80	0.50745	0.01607	632.41	48.06	988.65	1036.7	48.07	1048.0	1096.1	0.09328	1.94196	2.0352
85	0.59659	0.01609	542.80	53.06	985.28	1038.3	53.06	1045.2	1098.3	0.10248	1.91892	2.0214
90	0.69904	0.01610	467.40	58.05	981.90	1040.0	58.05	1042.4	1100.4	0.11161	1.89630	2.0079
95	0.81643	0.01612	403.74	63.04	978.52	1041.6	63.04	1039.5	1102.6	0.12065	1.87408	1.9947
100	0.95052	0.01613	349.83	68.03	975.14	1043.2	68.03	1036.7	1104.7	0.12961	1.85225	1.9819
110	1.2767	0.01617	264.96	78.01	968.36	1046.4	78.02	1031.0	1109.0	0.14728	1.80970	1.9570
120	1.6951	0.01620	202.94	88.00	961.56	1049.6	88.00	1025.2	1113.2	0.16466	1.76856	1.9332
130	2.2260	0.01625	157.09	97.99	954.73	1052.7	97.99	1019.4	1117.4	0.18174	1.72877	1.9105
140	2.8931	0.01629	122.81	107.98	947.87	1055.9	107.99	1013.6	1121.6	0.19855	1.69024	1.8888
150	3.7234	0.01634	96.929	117.98	940.98	1059.0	117.99	1007.8	1125.7	0.21508	1.65291	1.8680
160	4.7474	0.01639	77.185	127.98	934.05	1062.0	128.00	1001.8	1129.8	0.23136	1.61670	1.8481
170	5.9999	0.01645	61.982	138.00	927.08	1065.1	138.02	995.88	1133.9	0.24739	1.58155	1.8289
180	7.5197	0.01651	50.172	148.02	920.06	1068.1	148.04	989.85	1137.9	0.26318	1.54741	1.8106
190	9.3497	0.01657	40.920	158.05	912.99	1071.0	158.08	983.76	1141.8	0.27874	1.51421	1.7930
200	11.538	0.01663	33.613	168.10	905.87	1074.0	168.13	977.60	1145.7	0.29409	1.48191	1.7760
210	14.136	0.01670	27.798	178.15	898.68	1076.8	178.20	971.35	1149.5	0.30922	1.45046	1.7597
212	14.709	0.01671	26.782	180.16	897.24	1077.4	180.21	970.09	1150.3	0.31222	1.44427	1.7565
220	17.201	0.01677	23.136	188.22	891.43	1079.6	188.28	965.02	1153.3	0.32414	1.41980	1.7439
230	20.795	0.01684	19.374	198.31	884.10	1082.4	198.37	958.59	1157.0	0.33887	1.38989	1.7288
240	24.985	0.01692	16.316	208.41	876.70	1085.1	208.49	952.06	1160.5	0.35342	1.36069	1.7141
250	29.844	0.01700	13.816	218.54	869.21	1087.7	218.63	945.41	1164.0	0.36779	1.33216	1.6999
260	35.447	0.01708	11.760	228.68	861.62	1090.3	228.79	938.65	1167.4	0.38198	1.30425	1.6862
270	41.877	0.01717	10.059	238.85	853.94	1092.8	238.98	931.76	1170.7	0.39601	1.27694	1.6730
280	49.222	0.01726	8.6439	249.04	846.16	1095.2	249.20	924.74	1173.9	0.40989	1.25018	1.6601
290	57.573	0.01735	7.4607	259.26	838.27	1097.5	259.45	917.57	1177.0	0.42361	1.22393	1.6475
300	67.028	0.01745	6.4663	269.51	830.25	1099.8	269.73	910.24	1180.0	0.43720	1.19818	1.6354
310	77.691	0.01755	5.6266	279.79	822.11	1101.9	280.05	902.75	1182.8	0.45065	1.17289	1.6235
320	89.667	0.01765	4.9144	290.11	813.84	1104.0	290.40	895.09	1185.5	0.46396	1.14802	1.6120
330	103.07	0.01776	4.3076	300.46	805.43	1105.9	300.80	887.25	1188.1	0.47716	1.12355	1.6007
340	118.02	0.01787	3.7885	310.85	796.87	1107.7	311.24	879.22	1190.5	0.49024	1.09945	1.5897
350	134.63	0.01799	3.3425	321.29	788.16	1109.4	321.73	870.98	1192.7	0.50321	1.07570	1.5789
360	153.03	0.01811	2.9580	331.76	779.28	1111.0	332.28	862.53	1194.8	0.51607	1.05227	1.5683
370	173.36	0.01823	2.6252	342.29	770.23	1112.5	342.88	853.86	1196.7	0.52884	1.02914	1.5580
380	195.74	0.01836	2.3361	352.87	761.00	1113.9	353.53	844.96	1198.5	0.54152	1.00628	1.5478
390	220.33	0.01850	2.0842	363.50	751.58	1115.1	364.25	835.81	1200.1	0.55411	0.98366	1.5378

Saturated water—Temperature table (*Concluded*)

Temp., T °F	Sat. press., P_{sat} psia	Specific volume, ft³/lbm: Sat. liquid, v_f	Specific volume, ft³/lbm: Sat. vapor, v_g	Internal energy, Btu/lbm: Sat. liquid, u_f	Internal energy, Btu/lbm: Evap., u_{fg}	Internal energy, Btu/lbm: Sat. vapor, u_g	Enthalpy, Btu/lbm: Sat. liquid, h_f	Enthalpy, Btu/lbm: Evap., h_{fg}	Enthalpy, Btu/lbm: Sat. vapor, h_g	Entropy, Btu/lbm·R: Sat. liquid, s_f	Entropy, Btu/lbm·R: Evap., s_{fg}	Entropy, Btu/lbm·R: Sat. vapor, s_g
400	247.26	0.01864	1.8639	374.19	741.97	1116.2	375.04	826.39	1201.4	0.56663	0.96127	1.5279
410	276.69	0.01878	1.6706	384.94	732.14	1117.1	385.90	816.71	1202.6	0.57907	0.93908	1.5182
420	308.76	0.01894	1.5006	395.76	722.08	1117.8	396.84	806.74	1203.6	0.59145	0.91707	1.5085
430	343.64	0.01910	1.3505	406.65	711.80	1118.4	407.86	796.46	1204.3	0.60377	0.89522	1.4990
440	381.49	0.01926	1.2178	417.61	701.26	1118.9	418.97	785.87	1204.8	0.61603	0.87349	1.4895
450	422.47	0.01944	1.0999	428.66	690.47	1119.1	430.18	774.94	1205.1	0.62826	0.85187	1.4801
460	466.75	0.01962	0.99510	439.79	679.39	1119.2	441.48	763.65	1205.1	0.64044	0.83033	1.4708
470	514.52	0.01981	0.90158	451.01	668.02	1119.0	452.90	751.98	1204.9	0.65260	0.80885	1.4615
480	565.96	0.02001	0.81794	462.34	656.34	1118.7	464.43	739.91	1204.3	0.66474	0.78739	1.4521
490	621.24	0.02022	0.74296	473.77	644.32	1118.1	476.09	727.40	1203.5	0.67686	0.76594	1.4428
500	680.56	0.02044	0.67558	485.32	631.94	1117.3	487.89	714.44	1202.3	0.68899	0.74445	1.4334
510	744.11	0.02067	0.61489	496.99	619.17	1116.2	499.84	700.99	1200.8	0.70112	0.72290	1.4240
520	812.11	0.02092	0.56009	508.80	605.99	1114.8	511.94	687.01	1199.0	0.71327	0.70126	1.4145
530	884.74	0.02118	0.51051	520.76	592.35	1113.1	524.23	672.47	1196.7	0.72546	0.67947	1.4049
540	962.24	0.02146	0.46553	532.88	578.23	1111.1	536.70	657.31	1194.0	0.73770	0.65751	1.3952
550	1044.8	0.02176	0.42465	545.18	563.58	1108.8	549.39	641.47	1190.9	0.75000	0.63532	1.3853
560	1132.7	0.02207	0.38740	557.68	548.33	1106.0	562.31	624.91	1187.2	0.76238	0.61284	1.3752
570	1226.2	0.02242	0.35339	570.40	532.45	1102.8	575.49	607.55	1183.0	0.77486	0.59003	1.3649
580	1325.5	0.02279	0.32225	583.37	515.84	1099.2	588.95	589.29	1178.2	0.78748	0.56679	1.3543
590	1430.8	0.02319	0.29367	596.61	498.43	1095.0	602.75	570.04	1172.8	0.80026	0.54306	1.3433
600	1542.5	0.02362	0.26737	610.18	480.10	1090.3	616.92	549.67	1166.6	0.81323	0.51871	1.3319
610	1660.9	0.02411	0.24309	624.11	460.73	1084.8	631.52	528.03	1159.5	0.82645	0.49363	1.3201
620	1786.2	0.02464	0.22061	638.47	440.14	1078.6	646.62	504.92	1151.5	0.83998	0.46765	1.3076
630	1918.9	0.02524	0.19972	653.35	418.12	1071.5	662.32	480.07	1142.4	0.85389	0.44056	1.2944
640	2059.3	0.02593	0.18019	668.86	394.36	1063.2	678.74	453.14	1131.9	0.86828	0.41206	1.2803
650	2207.8	0.02673	0.16184	685.16	368.44	1053.6	696.08	423.65	1119.7	0.88332	0.38177	1.2651
660	2364.9	0.02767	0.14444	702.48	339.74	1042.2	714.59	390.84	1105.4	0.89922	0.34906	1.2483
670	2531.2	0.02884	0.12774	721.23	307.22	1028.5	734.74	353.54	1088.3	0.91636	0.31296	1.2293
680	2707.3	0.03035	0.11134	742.11	269.00	1011.1	757.32	309.57	1066.9	0.93541	0.27163	1.2070
690	2894.1	0.03255	0.09451	766.81	220.77	987.6	784.24	253.96	1038.2	0.95797	0.22089	1.1789
700	3093.0	0.03670	0.07482	801.75	146.50	948.3	822.76	168.32	991.1	0.99023	0.14514	1.1354
705.10	3200.1	0.04975	0.04975	866.61	0	866.6	896.07	0	896.1	1.05257	0	1.0526

Saturated water—Pressure table

Press., P psia	Sat. temp., T_{sat} °F	Specific volume, ft^3/lbm: Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, Btu/lbm: Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, Btu/lbm: Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Entropy, Btu/lbm·R: Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
1	101.69	0.01614	333.49	69.72	973.99	1043.7	69.72	1035.7	1105.4	0.13262	1.84495	1.9776
2	126.02	0.01623	173.71	94.02	957.45	1051.5	94.02	1021.7	1115.8	0.17499	1.74444	1.9194
3	141.41	0.01630	118.70	109.39	946.90	1056.3	109.40	1012.8	1122.2	0.20090	1.68489	1.8858
4	152.91	0.01636	90.629	120.89	938.97	1059.9	120.90	1006.0	1126.9	0.21985	1.64225	1.8621
5	162.18	0.01641	73.525	130.17	932.53	1062.7	130.18	1000.5	1130.7	0.23488	1.60894	1.8438
6	170.00	0.01645	61.982	138.00	927.08	1065.1	138.02	995.88	1133.9	0.24739	1.58155	1.8289
8	182.81	0.01652	47.347	150.83	918.08	1068.9	150.86	988.15	1139.0	0.26757	1.53800	1.8056
10	193.16	0.01659	38.425	161.22	910.75	1072.0	161.25	981.82	1143.1	0.28362	1.50391	1.7875
14.696	211.95	0.01671	26.805	180.12	897.27	1077.4	180.16	970.12	1150.3	0.31215	1.44441	1.7566
15	212.99	0.01672	26.297	181.16	896.52	1077.7	181.21	969.47	1150.7	0.31370	1.44441	1.7549
20	227.92	0.01683	20.093	196.21	885.63	1081.8	196.27	959.93	1156.2	0.33582	1.39606	1.7319
25	240.03	0.01692	16.307	208.45	876.67	1085.1	208.52	952.03	1160.6	0.35347	1.36060	1.7141
30	250.30	0.01700	13.749	218.84	868.98	1087.8	218.93	945.21	1164.1	0.36821	1.33132	1.6995
35	259.25	0.01708	11.901	227.92	862.19	1090.1	228.03	939.16	1167.2	0.38093	1.30632	1.6872
40	267.22	0.01715	10.501	236.02	856.09	1092.1	236.14	933.69	1169.8	0.39213	1.28448	1.6766
45	274.41	0.01721	9.4028	243.34	850.52	1093.9	243.49	928.68	1172.2	0.40216	1.26506	1.6672
50	280.99	0.01727	8.5175	250.05	845.39	1095.4	250.21	924.03	1174.2	0.41125	1.24756	1.6588
55	287.05	0.01732	7.7882	256.25	840.61	1096.9	256.42	919.70	1176.1	0.41958	1.23162	1.6512
60	292.69	0.01738	7.1766	262.01	836.13	1098.1	262.20	915.61	1177.8	0.42728	1.21697	1.6442
65	297.95	0.01743	6.6560	267.41	831.90	1099.3	267.62	911.75	1179.4	0.43443	1.20341	1.6378
70	302.91	0.01748	6.2075	272.50	827.90	1100.4	272.72	908.08	1180.8	0.44112	1.19078	1.6319
75	307.59	0.01752	5.8167	277.31	824.09	1101.4	277.55	904.58	1182.1	0.44741	1.17895	1.6264
80	312.02	0.01757	5.4733	281.87	820.45	1102.3	282.13	901.22	1183.4	0.45335	1.16783	1.6212
85	316.24	0.01761	5.1689	286.22	816.97	1103.2	286.50	898.00	1184.5	0.45897	1.15732	1.6163
90	320.26	0.01765	4.8972	290.38	813.62	1104.0	290.67	894.89	1185.6	0.46431	1.14737	1.6117
95	324.11	0.01770	4.6532	294.36	810.40	1104.8	294.67	891.89	1186.6	0.46941	1.13791	1.6073
100	327.81	0.01774	4.4327	298.19	807.29	1105.5	298.51	888.99	1187.5	0.47427	1.12888	1.6032
110	334.77	0.01781	4.0410	305.41	801.37	1106.8	305.78	883.44	1189.2	0.48341	1.11201	1.5954
120	341.25	0.01789	3.7289	312.16	795.79	1107.9	312.55	878.20	1190.8	0.49187	1.09646	1.5883
130	347.32	0.01796	3.4557	318.48	790.51	1109.0	318.92	873.21	1192.1	0.49974	1.08204	1.5818
140	353.03	0.01802	3.2202	324.45	785.49	1109.9	324.92	868.45	1193.4	0.50711	1.06858	1.5757
150	358.42	0.01809	3.0150	330.11	780.69	1110.8	330.61	863.88	1194.5	0.51405	1.05595	1.5700
160	363.54	0.01815	2.8347	335.49	776.10	1111.6	336.02	859.49	1195.5	0.52061	1.04405	1.5647
170	368.41	0.01821	2.6749	340.62	771.68	1112.3	341.19	855.25	1196.4	0.52682	1.03279	1.5596
180	373.07	0.01827	2.5322	345.53	767.42	1113.0	346.14	851.16	1197.3	0.53274	1.02210	1.5548
190	377.52	0.01833	2.4040	350.24	763.31	1113.6	350.89	847.19	1198.1	0.53839	1.01191	1.5503
200	381.80	0.01839	2.2882	354.78	759.32	1114.1	355.46	843.33	1198.8	0.54379	1.00219	1.5460
250	400.97	0.01865	1.8440	375.23	741.02	1116.3	376.09	825.47	1201.6	0.56784	0.95912	1.5270
300	417.35	0.01890	1.5435	392.89	724.77	1117.7	393.94	809.41	1203.3	0.58818	0.92289	1.5111
350	431.74	0.01912	1.3263	408.55	709.98	1118.5	409.79	794.65	1204.4	0.60590	0.89143	1.4973
400	444.62	0.01934	1.1617	422.70	696.31	1119.0	424.13	780.87	1205.0	0.62168	0.86350	1.4852
450	456.31	0.01955	1.0324	435.67	683.52	1119.2	437.30	767.86	1205.2	0.63595	0.83828	1.4742
500	467.04	0.01975	0.92819	447.68	671.42	1119.1	449.51	755.48	1205.0	0.64900	0.81521	1.4642
550	476.97	0.01995	0.84228	458.90	659.91	1118.8	460.93	743.60	1204.5	0.66107	0.79388	1.4550
600	486.24	0.02014	0.77020	469.46	648.88	1118.3	471.70	732.15	1203.9	0.67231	0.77400	1.4463
700	503.13	0.02051	0.65589	488.96	627.98	1116.9	491.62	710.29	1201.9	0.69279	0.73771	1.4305
800	518.27	0.02087	0.56920	506.74	608.30	1115.0	509.83	689.48	1199.3	0.71117	0.70502	1.4162

Saturated water—Pressure table (*Concluded*)

Press., P psia	Sat. temp., T_{sat} °F	Specific volume, ft^3/lbm Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, Btu/lbm Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, Btu/lbm Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Entropy, Btu/lbm·R Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
900	532.02	0.02124	0.50107	523.19	589.54	1112.7	526.73	669.46	1196.2	0.72793	0.67505	1.4030
1000	544.65	0.02159	0.44604	538.58	571.49	1110.1	542.57	650.03	1192.6	0.74341	0.64722	1.3906
1200	567.26	0.02232	0.36241	566.89	536.87	1103.8	571.85	612.39	1184.2	0.77143	0.59632	1.3677
1400	587.14	0.02307	0.30161	592.79	503.50	1096.3	598.76	575.66	1174.4	0.79658	0.54991	1.3465
1600	604.93	0.02386	0.25516	616.99	470.69	1087.7	624.06	539.18	1163.2	0.81972	0.50645	1.3262
1800	621.07	0.02470	0.21831	640.03	437.86	1077.9	648.26	502.35	1150.6	0.84144	0.46482	1.3063
2000	635.85	0.02563	0.18815	662.33	404.46	1066.8	671.82	464.60	1136.4	0.86224	0.42409	1.2863
2500	668.17	0.02860	0.13076	717.67	313.53	1031.2	730.90	360.79	1091.7	0.91311	0.31988	1.2330
3000	695.41	0.03433	0.08460	783.39	186.41	969.8	802.45	214.32	1016.8	0.97321	0.18554	1.1587
3200.1	705.10	0.04975	0.04975	866.61	0	866.6	896.07	0	896.1	1.05257	0	1.0526

APPENDIX B

Superheated water

T °F	v ft³/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm·R	v ft³/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm·R	v ft³/lbm	u Btu/lbm	h Btu/lbm	s Btu/ lbm·R
	P = 1.0 psia (101.69°F)*				P = 5.0 psia (162.18°F)				P = 10 psia (193.16°F)			
Sat.†	333.49	1043.7	1105.4	1.9776	73.525	1062.7	1130.7	1.8438	38.425	1072.0	1143.1	1.7875
200	392.53	1077.5	1150.1	2.0509	78.153	1076.2	1148.5	1.8716	38.849	1074.5	1146.4	1.7926
240	416.44	1091.2	1168.3	2.0777	83.009	1090.3	1167.1	1.8989	41.326	1089.1	1165.5	1.8207
280	440.33	1105.0	1186.5	2.1030	87.838	1104.3	1185.6	1.9246	43.774	1103.4	1184.4	1.8469
320	464.20	1118.9	1204.8	2.1271	92.650	1118.4	1204.1	1.9490	46.205	1117.6	1203.1	1.8716
360	488.07	1132.9	1223.3	2.1502	97.452	1132.5	1222.6	1.9722	48.624	1131.9	1221.8	1.8950
400	511.92	1147.1	1241.8	2.1722	102.25	1146.7	1241.3	1.9944	51.035	1146.2	1240.6	1.9174
440	535.77	1161.3	1260.4	2.1934	107.03	1160.9	1260.0	2.0156	53.441	1160.5	1259.4	1.9388
500	571.54	1182.8	1288.6	2.2237	114.21	1182.6	1288.2	2.0461	57.041	1182.2	1287.8	1.9693
600	631.14	1219.4	1336.2	2.2709	126.15	1219.2	1335.9	2.0933	63.029	1219.0	1335.6	2.0167
700	690.73	1256.8	1384.6	2.3146	138.09	1256.7	1384.4	2.1371	69.007	1256.5	1384.2	2.0605
800	750.31	1295.1	1433.9	2.3553	150.02	1294.9	1433.7	2.1778	74.980	1294.8	1433.5	2.1013
1000	869.47	1374.2	1535.1	2.4299	173.86	1374.2	1535.0	2.2524	86.913	1374.1	1534.9	2.1760
1200	988.62	1457.1	1640.0	2.4972	197.70	1457.0	1640.0	2.3198	98.840	1457.0	1639.9	2.2433
1400	1107.8	1543.7	1748.7	2.5590	221.54	1543.7	1748.7	2.3816	110.762	1543.6	1748.6	2.3052
	P = 15 psia (212.99°F)				P = 20 psia (227.92°F)				P = 40 psia (267.22°F)			
Sat.	26.297	1077.7	1150.7	1.7549	20.093	1081.8	1156.2	1.7319	10.501	1092.1	1169.8	1.6766
240	27.429	1087.8	1163.9	1.7742	20.478	1086.5	1162.3	1.7406				
280	29.085	1102.4	1183.2	1.8010	21.739	1101.4	1181.9	1.7679	10.713	1097.3	1176.6	1.6858
320	30.722	1116.9	1202.2	1.8260	22.980	1116.1	1201.2	1.7933	11.363	1112.9	1197.1	1.7128
360	32.348	1131.3	1221.1	1.8496	24.209	1130.7	1220.2	1.8171	11.999	1128.1	1216.9	1.7376
400	33.965	1145.7	1239.9	1.8721	25.429	1145.1	1239.3	1.8398	12.625	1143.1	1236.5	1.7610
440	35.576	1160.1	1258.8	1.8936	26.644	1159.7	1258.3	1.8614	13.244	1157.9	1256.0	1.7831
500	37.986	1181.9	1287.3	1.9243	28.458	1181.6	1286.9	1.8922	14.165	1180.2	1285.0	1.8143
600	41.988	1218.7	1335.3	1.9718	31.467	1218.5	1334.9	1.9398	15.686	1217.5	1333.6	1.8625
700	45.981	1256.3	1383.9	2.0156	34.467	1256.1	1383.7	1.9837	17.197	1255.3	1382.6	1.9067
800	49.967	1294.6	1433.3	2.0565	37.461	1294.5	1433.1	2.0247	18.702	1293.9	1432.3	1.9478
1000	57.930	1374.0	1534.8	2.1312	43.438	1373.8	1534.6	2.0994	21.700	1373.4	1534.1	2.0227
1200	65.885	1456.9	1639.8	2.1986	49.407	1456.8	1639.7	2.1668	24.691	1456.5	1639.3	2.0902
1400	73.836	1543.6	1748.5	2.2604	55.373	1543.5	1748.4	2.2287	27.678	1543.3	1748.1	2.1522
1600	81.784	1634.0	1861.0	2.3178	61.335	1633.9	1860.9	2.2861	30.662	1633.7	1860.7	2.2096
	P = 60 psia (292.69°F)				P = 80 psia (312.02°F)				P = 100 psia (327.81°F)			
Sat.	7.1766	1098.1	1177.8	1.6442	5.4733	1102.3	1183.4	1.6212	4.4327	1105.5	1187.5	1.6032
320	7.4863	1109.6	1192.7	1.6636	5.5440	1105.9	1187.9	1.6271				
360	7.9259	1125.5	1213.5	1.6897	5.8876	1122.7	1209.9	1.6545	4.6628	1119.8	1206.1	1.6263
400	8.3548	1140.9	1233.7	1.7138	6.2187	1138.7	1230.8	1.6794	4.9359	1136.4	1227.8	1.6521
440	8.7766	1156.1	1253.6	1.7364	6.5420	1154.3	1251.2	1.7026	5.2006	1152.4	1248.7	1.6759
500	9.4005	1178.8	1283.1	1.7682	7.0177	1177.3	1281.2	1.7350	5.5876	1175.9	1279.3	1.7088
600	10.4256	1216.5	1332.2	1.8168	7.7951	1215.4	1330.8	1.7841	6.2167	1214.4	1329.4	1.7586
700	11.4401	1254.5	1381.6	1.8613	8.5616	1253.8	1380.5	1.8289	6.8344	1253.0	1379.5	1.8037
800	12.4484	1293.3	1431.5	1.9026	9.3218	1292.6	1430.6	1.8704	7.4457	1292.0	1429.8	1.8453
1000	14.4543	1373.0	1533.5	1.9777	10.8313	1372.6	1532.9	1.9457	8.6575	1372.2	1532.4	1.9208
1200	16.4525	1456.2	1638.9	2.0454	12.3331	1455.9	1638.5	2.0135	9.8615	1455.6	1638.1	1.9887
1400	18.4464	1543.0	1747.8	2.1073	13.8306	1542.8	1747.5	2.0755	11.0612	1542.6	1747.2	2.0508
1600	20.438	1633.5	1860.5	2.1648	15.3257	1633.3	1860.2	2.1330	12.2584	1633.2	1860.0	2.1083
1800	22.428	1727.6	1976.6	2.2187	16.8192	1727.5	1976.5	2.1869	13.4541	1727.3	1976.3	2.1622
2000	24.417	1825.2	2096.3	2.2694	18.3117	1825.0	2096.1	2.2376	14.6487	1824.9	2096.0	2.2130

Superheated water (*Concluded*)

T °F	*v* ft³/lbm	*u* Btu/lbm	*h* Btu/lbm	*s* Btu/lbm·R	*v* ft³/lbm	*u* Btu/lbm	*h* Btu/lbm	*s* Btu/lbm·R	*v* ft³/lbm	*u* Btu/lbm	*h* Btu/lbm	*s* Btu/ lbm·R
	P = 120 psia (341.25°F)				*P* = 140 psia (353.03°F)				*P* = 160 psia (363.54°F)			
Sat.	3.7289	1107.9	1190.8	1.5883	3.2202	1109.9	1193.4	1.5757	2.8347	1111.6	1195.5	1.5647
360	3.8446	1116.7	1202.1	1.6023	3.2584	1113.4	1197.8	1.5811				
400	4.0799	1134.0	1224.6	1.6292	3.4676	1131.5	1221.4	1.6092	3.0076	1129.0	1218.0	1.5914
450	4.3613	1154.5	1251.4	1.6594	3.7147	1152.6	1248.9	1.6403	3.2293	1150.7	1246.3	1.6234
500	4.6340	1174.4	1277.3	1.6872	3.9525	1172.9	1275.3	1.6686	3.4412	1171.4	1273.2	1.6522
550	4.9010	1193.9	1302.8	1.7131	4.1845	1192.7	1301.1	1.6948	3.6469	1191.4	1299.4	1.6788
600	5.1642	1213.4	1328.0	1.7375	4.4124	1212.3	1326.6	1.7195	3.8484	1211.3	1325.2	1.7037
700	5.6829	1252.2	1378.4	1.7829	4.8604	1251.4	1377.3	1.7652	4.2434	1250.6	1376.3	1.7498
800	6.1950	1291.4	1429.0	1.8247	5.3017	1290.8	1428.1	1.8072	4.6316	1290.2	1427.3	1.7920
1000	7.2083	1371.7	1531.8	1.9005	6.1732	1371.3	1531.3	1.8832	5.3968	1370.9	1530.7	1.8682
1200	8.2137	1455.3	1637.7	1.9684	7.0367	1455.0	1637.3	1.9512	6.1540	1454.7	1636.9	1.9363
1400	9.2149	1542.3	1746.9	2.0305	7.8961	1542.1	1746.6	2.0134	6.9070	1541.8	1746.3	1.9986
1600	10.2135	1633.0	1859.8	2.0881	8.7529	1632.8	1859.5	2.0711	7.6574	1632.6	1859.3	2.0563
1800	11.2106	1727.2	1976.1	2.1420	9.6082	1727.0	1975.9	2.1250	8.4063	1726.9	1975.7	2.1102
2000	12.2067	1824.8	2095.8	2.1928	10.4624	1824.6	2095.7	2.1758	9.1542	1824.5	2095.5	2.1610
	P = 180 psia (373.07°F)				*P* = 200 psia (381.80°F)				*P* = 225 psia (391.80°F)			
Sat.	2.5322	1113.0	1197.3	1.5548	2.2882	1114.1	1198.8	1.5460	2.0423	1115.3	1200.3	1.5360
400	2.6490	1126.3	1214.5	1.5752	2.3615	1123.5	1210.9	1.5602	2.0728	1119.7	1206.0	1.5427
450	2.8514	1148.7	1243.7	1.6082	2.5488	1146.7	1241.0	1.5943	2.2457	1144.1	1237.6	1.5783
500	3.0433	1169.8	1271.2	1.6376	2.7247	1168.2	1269.0	1.6243	2.4059	1166.2	1266.3	1.6091
550	3.2286	1190.2	1297.7	1.6646	2.8939	1188.9	1296.0	1.6516	2.5590	1187.2	1293.8	1.6370
600	3.4097	1210.2	1323.8	1.6897	3.0586	1209.1	1322.3	1.6771	2.7075	1207.7	1320.5	1.6628
700	3.7635	1249.8	1375.2	1.7361	3.3796	1249.0	1374.1	1.7238	2.9956	1248.0	1372.7	1.7099
800	4.1104	1289.5	1426.5	1.7785	3.6934	1288.9	1425.6	1.7664	3.2765	1288.1	1424.5	1.7528
900	4.4531	1329.7	1478.0	1.8179	4.0031	1329.2	1477.3	1.8059	3.5530	1328.5	1476.5	1.7925
1000	4.7929	1370.5	1530.1	1.8549	4.3099	1370.1	1529.6	1.8430	3.8268	1369.5	1528.9	1.8296
1200	5.4674	1454.3	1636.5	1.9231	4.9182	1454.0	1636.1	1.9113	4.3689	1453.6	1635.6	1.8981
1400	6.1377	1541.6	1746.0	1.9855	5.5222	1541.4	1745.7	1.9737	4.9068	1541.1	1745.4	1.9606
1600	6.8054	1632.4	1859.1	2.0432	6.1238	1632.2	1858.8	2.0315	5.4422	1632.0	1858.6	2.0184
1800	7.4716	1726.7	1975.6	2.0971	6.7238	1726.5	1975.4	2.0855	5.9760	1726.4	1975.2	2.0724
2000	8.1367	1824.4	2095.4	2.1479	7.3227	1824.3	2095.3	2.1363	6.5087	1824.1	2095.1	2.1232
	P = 250 psia (400.97°F)				*P* = 275 psia (409.45°F)				*P* = 300 psia (417.35°F)			
Sat.	1.8440	1116.3	1201.6	1.5270	1.6806	1117.0	1202.6	1.5187	1.5435	1117.7	1203.3	1.5111
450	2.0027	1141.3	1234.0	1.5636	1.8034	1138.5	1230.3	1.5499	1.6369	1135.6	1226.4	1.5369
500	2.1506	1164.1	1263.6	1.5953	1.9415	1162.0	1260.8	1.5825	1.7670	1159.8	1257.9	1.5706
550	2.2910	1185.6	1291.5	1.6237	2.0715	1183.9	1289.3	1.6115	1.8885	1182.1	1287.0	1.6001
600	2.4264	1206.3	1318.6	1.6499	2.1964	1204.9	1316.7	1.6380	2.0046	1203.5	1314.8	1.6270
650	2.5586	1226.8	1345.1	1.6743	2.3179	1225.6	1343.5	1.6627	2.1172	1224.4	1341.9	1.6520
700	2.6883	1247.0	1371.4	1.6974	2.4369	1246.0	1370.0	1.6860	2.2273	1244.9	1368.6	1.6755
800	2.9429	1287.3	1423.5	1.7406	2.6699	1286.5	1422.4	1.7294	2.4424	1285.7	1421.3	1.7192
900	3.1930	1327.9	1475.6	1.7804	2.8984	1327.3	1474.8	1.7694	2.6529	1326.6	1473.9	1.7593
1000	3.4403	1369.0	1528.2	1.8177	3.1241	1368.5	1527.4	1.8068	2.8605	1367.9	1526.7	1.7968
1200	3.9295	1453.3	1635.0	1.8863	3.5700	1452.9	1634.5	1.8755	3.2704	1452.5	1634.0	1.8657
1400	4.4144	1540.8	1745.0	1.9488	4.0116	1540.5	1744.6	1.9381	3.6759	1540.2	1744.2	1.9284
1600	4.8969	1631.7	1858.3	2.0066	4.4507	1631.5	1858.0	1.9960	4.0789	1631.3	1857.7	1.9863
1800	5.3777	1726.2	1974.9	2.0607	4.8882	1726.0	1974.7	2.0501	4.4803	1725.8	1974.5	2.0404
2000	5.8575	1823.9	2094.9	2.1116	5.3247	1823.8	2094.7	2.1010	4.8807	1823.6	2094.6	2.0913

Superheated water *(Continued)*

T °F	v ft³/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm·R	v ft³/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm·R	v ft³/lbm	u Btu/lbm	h Btu/lbm	s Btu/ lbm·R
	P = 350 psia (431.74°F)				P = 400 psia (444.62°F)				P = 450 psia (456.31°F)			
Sat.	1.3263	1118.5	1204.4	1.4973	1.1617	1119.0	1205.0	1.4852	1.0324	1119.2	1205.2	1.4742
450	1.3739	1129.3	1218.3	1.5128	1.1747	1122.5	1209.4	1.4901				
500	1.4921	1155.2	1251.9	1.5487	1.2851	1150.4	1245.6	1.5288	1.1233	1145.4	1238.9	1.5103
550	1.6004	1178.6	1282.2	1.5795	1.3840	1174.9	1277.3	1.5610	1.2152	1171.1	1272.3	1.5441
600	1.7030	1200.6	1310.9	1.6073	1.4765	1197.6	1306.9	1.5897	1.3001	1194.6	1302.8	1.5737
650	1.8018	1221.9	1338.6	1.6328	1.5650	1219.4	1335.3	1.6158	1.3807	1216.9	1331.9	1.6005
700	1.8979	1242.8	1365.8	1.6567	1.6507	1240.7	1362.9	1.6401	1.4584	1238.5	1360.0	1.6253
800	2.0848	1284.1	1419.1	1.7009	1.8166	1282.5	1417.0	1.6849	1.6080	1280.8	1414.7	1.6706
900	2.2671	1325.3	1472.2	1.7414	1.9777	1324.0	1470.4	1.7257	1.7526	1322.7	1468.6	1.7117
1000	2.4464	1366.9	1525.3	1.7791	2.1358	1365.8	1523.9	1.7636	1.8942	1364.7	1522.4	1.7499
1200	2.7996	1451.7	1633.0	1.8483	2.4465	1450.9	1632.0	1.8331	2.1718	1450.1	1631.0	1.8196
1400	3.1484	1539.6	1743.5	1.9111	2.7527	1539.0	1742.7	1.8960	2.4450	1538.4	1742.0	1.8827
1600	3.4947	1630.8	1857.1	1.9691	3.0565	1630.3	1856.5	1.9541	2.7157	1629.8	1856.0	1.9409
1800	3.8394	1725.4	1974.0	2.0233	3.3586	1725.0	1973.6	2.0084	2.9847	1724.6	1973.2	1.9952
2000	4.1830	1823.3	2094.2	2.0742	3.6597	1823.0	2093.9	2.0594	3.2527	1822.6	2093.5	2.0462
	P = 500 psia (467.04°F)				P = 600 psia (486.24°F)				P = 700 psia (503.13°F)			
Sat.	0.92815	1119.1	1205.0	1.4642	0.77020	1118.3	1203.9	1.4463	0.65589	1116.9	1201.9	1.4305
500	0.99304	1140.1	1231.9	1.4928	0.79526	1128.2	1216.5	1.4596				
550	1.07974	1167.1	1267.0	1.5284	0.87542	1158.7	1255.9	1.4996	0.72799	1149.5	1243.8	1.4730
600	1.15876	1191.4	1298.6	1.5590	0.94605	1184.9	1289.9	1.5325	0.79332	1177.9	1280.7	1.5087
650	1.23312	1214.3	1328.4	1.5865	1.01133	1209.0	1321.3	1.5614	0.85242	1203.4	1313.8	1.5393
700	1.30440	1236.4	1357.0	1.6117	1.07316	1231.9	1351.0	1.5877	0.90769	1227.2	1344.8	1.5666
800	1.44097	1279.2	1412.5	1.6576	1.19038	1275.8	1408.0	1.6348	1.01125	1272.4	1403.4	1.6150
900	1.57252	1321.4	1466.9	1.6992	1.30230	1318.7	1463.3	1.6771	1.10921	1316.0	1459.7	1.6581
1000	1.70094	1363.6	1521.0	1.7376	1.41097	1361.4	1518.1	1.7160	1.20381	1359.2	1515.2	1.6974
1100	1.82726	1406.2	1575.3	1.7735	1.51749	1404.4	1572.9	1.7522	1.29621	1402.5	1570.4	1.7341
1200	1.95211	1449.4	1630.0	1.8075	1.62252	1447.8	1627.9	1.7865	1.38709	1446.2	1625.9	1.7685
1400	2.1988	1537.8	1741.2	1.8708	1.82957	1536.6	1739.7	1.8501	1.56580	1535.4	1738.2	1.8324
1600	2.4430	1629.4	1855.4	1.9291	2.0340	1628.4	1854.2	1.9085	1.74192	1627.5	1853.1	1.8911
1800	2.6856	1724.2	1972.7	1.9834	2.2369	1723.4	1971.8	1.9630	1.91643	1722.7	1970.9	1.9457
2000	2.9271	1822.3	2093.1	2.0345	2.4387	1821.7	2092.4	2.0141	2.08987	1821.0	2091.7	1.9969
	P = 800 psia (518.27°F)				P = 1000 psia (544.65°F)				P = 1250 psia (572.45°F)			
Sat.	0.56920	1115.0	1199.3	1.4162	0.44604	1110.1	1192.6	1.3906	0.34549	1102.0	1181.9	1.3623
550	0.61586	1139.4	1230.5	1.4476	0.45375	1115.2	1199.2	1.3972				
600	0.67799	1170.5	1270.9	1.4866	0.51431	1154.1	1249.3	1.4457	0.37894	1129.5	1217.2	1.3961
650	0.73279	1197.6	1306.0	1.5191	0.56411	1185.1	1289.5	1.4827	0.42703	1167.5	1266.3	1.4414
700	0.78330	1222.4	1338.4	1.5476	0.60844	1212.4	1325.0	1.5140	0.46735	1198.7	1306.8	1.4771
750	0.83102	1246.0	1369.1	1.5735	0.64944	1237.6	1357.8	1.5418	0.50344	1226.4	1342.9	1.5076
800	0.87678	1268.9	1398.7	1.5975	0.68821	1261.7	1389.0	1.5670	0.53687	1252.2	1376.4	1.5347
900	0.96434	1313.3	1456.0	1.6413	0.76136	1307.7	1448.6	1.6126	0.59876	1300.5	1439.0	1.5826
1000	1.04841	1357.0	1512.2	1.6812	0.83078	1352.5	1506.2	1.6535	0.65656	1346.7	1498.6	1.6249
1100	1.13024	1400.7	1568.0	1.7181	0.89783	1396.9	1563.1	1.6911	0.71184	1392.2	1556.8	1.6635
1200	1.21051	1444.6	1623.8	1.7528	0.96327	1441.4	1619.7	1.7263	0.76545	1437.4	1614.5	1.6993
1400	1.36797	1534.2	1736.7	1.8170	1.09101	1531.8	1733.7	1.7911	0.86944	1528.7	1729.8	1.7649
1600	1.52283	1626.5	1851.9	1.8759	1.21610	1624.6	1849.6	1.8504	0.97072	1622.2	1846.7	1.8246
1800	1.67606	1721.9	1970.0	1.9306	1.33956	1720.3	1968.2	1.9053	1.07036	1718.4	1966.0	1.8799
2000	1.82823	1820.4	2091.0	1.9819	1.46194	1819.1	2089.6	1.9568	1.16892	1817.5	2087.9	1.9315

Superheated water (*Concluded*)

T °F	*v* ft³/lbm	*u* Btu/lbm	*h* Btu/lbm	*s* Btu/lbm·R	*v* ft³/lbm	*u* Btu/lbm	*h* Btu/lbm	*s* Btu/lbm·R	*v* ft³/lbm	*u* Btu/lbm	*h* Btu/lbm	*s* Btu/ lbm·R
	P = 1500 psia (596.26°F)				*P* = 1750 psia (617.17°F)				*P* = 2000 psia (635.85°F)			
Sat.	0.27695	1092.1	1169.0	1.3362	0.22681	1080.5	1153.9	1.3112	0.18815	1066.8	1136.4	1.2863
600	0.28189	1097.2	1175.4	1.3423								
650	0.33310	1147.2	1239.7	1.4016	0.26292	1122.8	1207.9	1.3607	0.20586	1091.4	1167.6	1.3146
700	0.37198	1183.6	1286.9	1.4433	0.30252	1166.8	1264.7	1.4108	0.24894	1147.6	1239.8	1.3783
750	0.40535	1214.4	1326.9	1.4771	0.33455	1201.5	1309.8	1.4489	0.28074	1187.4	1291.3	1.4218
800	0.43550	1242.2	1363.1	1.5064	0.36266	1231.7	1349.1	1.4807	0.30763	1220.5	1334.3	1.4567
850	0.46356	1268.2	1396.9	1.5328	0.38835	1259.3	1385.1	1.5088	0.33169	1250.0	1372.8	1.4867
900	0.49015	1293.1	1429.2	1.5569	0.41238	1285.4	1419.0	1.5341	0.35390	1277.5	1408.5	1.5134
1000	0.54031	1340.9	1490.8	1.6007	0.45719	1334.9	1482.9	1.5796	0.39479	1328.7	1474.9	1.5606
1100	0.58781	1387.3	1550.5	1.6402	0.49917	1382.4	1544.1	1.6201	0.43266	1377.5	1537.6	1.6021
1200	0.63355	1433.3	1609.2	1.6767	0.53932	1429.2	1603.9	1.6572	0.46864	1425.1	1598.5	1.6400
1400	0.72172	1525.7	1726.0	1.7432	0.61621	1522.6	1722.1	1.7245	0.53708	1519.5	1718.3	1.7081
1600	0.80714	1619.8	1843.8	1.8033	0.69031	1617.4	1840.9	1.7852	0.60269	1615.0	1838.0	1.7693
1800	0.89090	1716.4	1963.7	1.8589	0.76273	1714.5	1961.5	1.8410	0.66660	1712.5	1959.2	1.8255
2000	0.97358	1815.9	2086.1	1.9108	0.83406	1814.2	2084.3	1.8931	0.72942	1812.6	2082.6	1.8778
	P = 2500 psia (668.17°F)				*P* = 3000 psia (695.41°F)				*P* = 3500 psia			
Sat.	0.13076	1031.2	1091.7	1.2330	0.08460	969.8	1016.8	1.1587				
650									0.02492	663.7	679.9	0.8632
700	0.16849	1098.4	1176.3	1.3072	0.09838	1005.3	1059.9	1.1960	0.03065	760.0	779.9	0.9511
750	0.20327	1154.9	1249.0	1.3686	0.14840	1114.1	1196.5	1.3118	0.10460	1057.6	1125.4	1.2434
800	0.22949	1195.9	1302.0	1.4116	0.17601	1167.5	1265.3	1.3676	0.13639	1134.3	1222.6	1.3224
850	0.25174	1230.1	1346.6	1.4463	0.19771	1208.2	1317.9	1.4086	0.15847	1183.8	1286.5	1.3721
900	0.27165	1260.7	1386.4	1.4761	0.21640	1242.8	1362.9	1.4423	0.17659	1223.4	1337.8	1.4106
950	0.29001	1289.1	1423.3	1.5028	0.23321	1273.9	1403.3	1.4716	0.19245	1257.8	1382.4	1.4428
1000	0.30726	1316.1	1458.2	1.5271	0.24876	1302.8	1440.9	1.4978	0.20687	1289.0	1423.0	1.4711
1100	0.33949	1367.3	1524.4	1.5710	0.27732	1356.8	1510.8	1.5441	0.23289	1346.1	1496.9	1.5201
1200	0.36966	1416.6	1587.6	1.6103	0.30367	1408.0	1576.6	1.5850	0.25654	1399.3	1565.4	1.5627
1400	0.42631	1513.3	1710.5	1.6802	0.35249	1507.0	1702.7	1.6567	0.29978	1500.7	1694.8	1.6364
1600	0.48004	1610.1	1832.2	1.7424	0.39830	1605.3	1826.4	1.7199	0.33994	1600.4	1820.5	1.7006
1800	0.53205	1708.6	1954.8	1.7991	0.44237	1704.7	1950.3	1.7773	0.37833	1700.8	1945.8	1.7586
2000	0.58295	1809.4	2079.1	1.8518	0.48532	1806.1	2075.6	1.8304	0.41561	1802.9	2072.1	1.8121
	P = 4000 psia				*P* = 5000 psia				*P* = 6000 psia			
650	0.02448	657.9	676.1	0.8577	0.02379	648.3	670.3	0.8485	0.02325	640.3	666.1	0.8408
700	0.02871	742.3	763.6	0.9347	0.02678	721.8	746.6	0.9156	0.02564	708.1	736.5	0.9028
750	0.06370	962.1	1009.2	1.1410	0.03373	821.8	853.0	1.0054	0.02981	788.7	821.8	0.9747
800	0.10520	1094.2	1172.1	1.2734	0.05937	986.9	1041.8	1.1581	0.03949	897.1	941.0	1.0711
850	0.12848	1156.7	1251.8	1.3355	0.08551	1092.4	1171.5	1.2593	0.05815	1018.6	1083.1	1.1819
900	0.14647	1202.5	1310.9	1.3799	0.10390	1155.9	1252.1	1.3198	0.07584	1103.5	1187.7	1.2603
950	0.16176	1240.7	1360.5	1.4157	0.11863	1203.9	1313.6	1.3643	0.09010	1163.7	1263.7	1.3153
1000	0.17538	1274.6	1404.4	1.4463	0.13128	1244.0	1365.5	1.4004	0.10208	1211.4	1324.7	1.3578
1100	0.19957	1335.1	1482.8	1.4983	0.15298	1312.2	1453.8	1.4590	0.12211	1288.4	1424.0	1.4237
1200	0.22121	1390.3	1554.1	1.5426	0.17185	1372.1	1531.1	1.5070	0.13911	1353.4	1507.8	1.4758
1300	0.24128	1443.0	1621.6	1.5821	0.18902	1427.8	1602.7	1.5490	0.15434	1412.5	1583.8	1.5203
1400	0.26028	1494.3	1687.0	1.6182	0.20508	1481.4	1671.1	1.5868	0.16841	1468.4	1655.4	1.5598
1600	0.29620	1595.5	1814.7	1.6835	0.23505	1585.6	1803.1	1.6542	0.19438	1575.7	1791.5	1.6294
1800	0.33033	1696.8	1941.4	1.7422	0.26320	1689.0	1932.5	1.7142	0.21853	1681.1	1923.7	1.6907
2000	0.36335	1799.7	2068.6	1.7961	0.29023	1793.2	2061.7	1.7689	0.24155	1786.7	2054.9	1.7463