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The Relation between Air Ejector and Vacuum Pump Operation to Minimize Turbine Back Pressure

Case study in Khartoum North Power Station (KNPS)

العلاقة بين تشغيل قاذف الهواء والمضخة التفريغية لتقليل الضغط الخلفي للتوربين

دراسة حالة في محطة بحري الحرارية

Submitted as partial fulfillment for the degree of B.Eng (Honor)

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الآية:-

﴿ وما أوتيتم من العلم إلا قليلا ﴾

الإهداء

إلى كل من أضاء بعلمه العقول

ووضع في دروبنا الشموع

ليرى هذا العمل النور

إلى أمي وأبي

أهدي هذا العمل المتواضع

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To the great Sudan University of Science and Technology and to the staff of mechanical engineering department.

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Abstract

The utilization of the thermal power generation is always related to the presence of non-condensable gases, as a natural components of the steam. For this reason, it is necessary to remove these elements in order to improve the thermodynamic efficiency of thermal power plants.

In practical applications there are two main equipment's for this task, which are: steam ejectors and liquid ring vacuum pumps.

This case study deals with the parameters which affects the performance of this vacuum system, how to keep back pressure at constant value, and correcting the size of air extraction system.

This study concluded that the air extraction system preserve the back pressure at constant range, also when the back pressure increased this causes an increase in fuel consumption for the same power output.

المستخلص

الإستفادة من الطاقة الحرارية للبخار دائما ما يرتبط بوجود الهواء والغازات الغير متكثفة الموجودة في البخار لهذا السبب من الضروري إزالة هذه الغازات لتحسين الكفاءة الحرارية في محطات التوليد الحرارية.

في التطبيقات العملية هنالك نوعان من المعدات الرئيسية المستخدمة في هذا المجال وهي قاذفات الهواء البخارية، والمضخة التفريغية.

هذه الدراسة الوصفية تهدف لدراسة الخواص التشغيلية والمحيطة التي تؤثر على أداء النظم التفريغية وكيفية المحافظة على الضغط الخلفي للتوربين في حدود ثابتة. وتصحيح سعة المضخة التفريغية.

خلصت الدراسة إلى أن النظم التفريغية تساعد على تثبيت الضغط الخلفي للتوربين بثبات بقية الظروف التشغيلية، وأيضا زيادة الضغط الخلفي للتوربين تؤدي لزيادة استهلاك الوقود عند نفس القدرة الخارجة.

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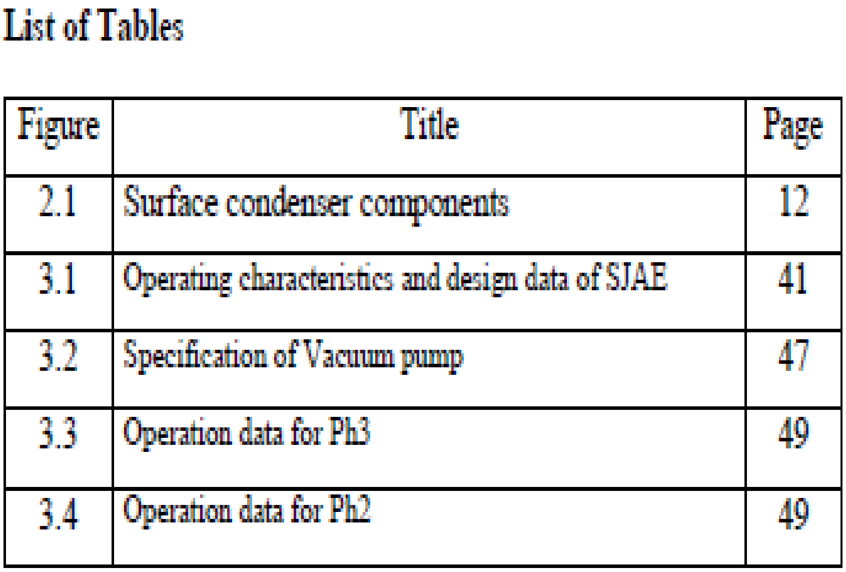

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Chapter one

Introduction

1-1 Introduction:

Electricity is a major player in our society as it has significantly improved the quality of life for all of those who use it.

Most of the electricity being produced throughout the world today is from steam power plants. At the same time, many other competent means of generating electricity have been developed viz. electricity from natural gas, MHD generators, biogas, solar cells, etc.

Steam is extremely valuable because it can be produced anywhere in the world by using the heat that comes from the fuels that are available in the area. Steam also has unique properties that are extremely important in producing energy. Steam is basically recycled, from steam to water and then back to steam again, all in manner that nontoxic in nature.

The steam power plants of today are a combination of complex engineered systems that work to produce steam in manner that is economically feasible.

But steam power plants will continue to be competent, because of the use of water as the main working fluid which is abundantly available and is also reusable.

The Rankine cycle is standard for steam power plants around the world. The basic Rankine cycle used in a steam power plant consists of the following main components: 1. Steam generator; 2. Turbine; 3. Steam condenser; and 4. Pump. The actual Rankine cycle used in a modern steam power plant has many more components, but the above components are common to all power plants.

In this cycle, water is heated in the steam generator to produce a high temperature and high pressure steam. This steam is expanded in a turbine connected to an electricity generator. The exit steam from the turbine is condensed back to water in the condenser. The pump then returns the water to the steam generator. Thus, the main purpose of the condenser is to condense the exhaust steam from the turbine for reuse in the cycle, and to maximize turbine efficiency by maintaining a proper vacuum.

The condenser remains among one of the key components of a steam power plant. The efficiency of a thermal power plant depends upon the efficiency of the condenser.

As the operating pressure of the condenser is low due to an increased vacuum, the enthalpy drop of the expanding steam in the turbine will increase. This increases the amount of available work from the turbine. The low condenser operating pressure enables higher turbine output, an increase in plant efficiency and reduced steam flow for a given plant output. It is, therefore, advantageous to operate the condenser at the lowest possible pressure (highest vacuum).

A vacuum is produced in the condenser by the condensation process and the specific volume change from steam to a liquid. A low condenser vacuum corresponds to a low steam saturation temperature. The total work done by steam flow through the turbine is proportional to the difference between the temperature of steam entering the turbine and the saturation temperature in the condenser.

Therefore, the lower the saturation temperature, the more work that is done by the steam in the turbine. The more work that is done in the turbine, the greater the thermal efficiency and output of the turbine.

But there are several parameters that effect on condenser vacuum, likes air leakage, and non-condensable gases, cleanness of CW tubes…etc.

Then to achieve the desired vacuum, you must put the condenser in the optimal conditions. And try to reduce the undesirable factors.

1.2 Research objectives:

1-Increase the thermal efficiency of KNPS, by keeping the condenser in a constant pressure.

2-Correcting the size of air extraction system, corresponding to the HEI's standard.

1.3 Methodology:

Theoretical study of surface condenser and its main components will done depend on multi references in power plant technology, and website concerning Surface condenser and air removal equipment, there will be several visits to **Dr. Sheriff** power station; data concerning surface condenser, vacuum equipment, and the cooling system will be collected, then the thermal efficiencies will be calculated, to show the effect of air extraction equipment's operation. Also optimizing and correcting the size of the air extraction pump.

Chapter two

Literature review

2.1 Condenser:

From the expression of Carnot cycle thermal efficiency $\eta=1-\frac{T2}{T1}$, we know that if we want to increase the thermal efficiency we must decrease T2 (temperature at which heat is rejected).

Low exhaust pressure is necessary to obtain low exhaust temperature. But the steam cannot be exhausted to the atmosphere if it is expanded in the engine or turbine to a pressure lower than the atmospheric pressure. Under this condition, the steam is exhausted into a vessel known as condenser where the pressure is maintained below the atmosphere by continuously condensing the steam by means of circulating cold water at atmospheric temperature. [1]

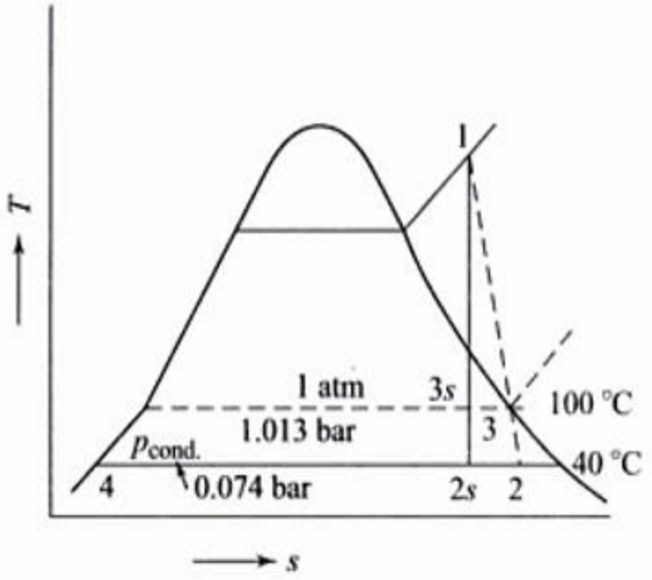
Then we can define condenser as a heat transfer device or unit used to condense a substance from its gaseous to its liquid state, typically by cooling it. In doing so, the latent heat is given up by the substance, and will transfer to the condenser coolant. Use of cooling water or surrounding air as the coolant is common in many condensers. [At all]

2.1.1 Need of condenser:

Condensing power plants are much more efficient than noncondensing ones, all modern power plants are of the condensing type. A condenser is a major and very important equipment in the power plant.

Its serves three purposes:

1- The main function of the condenser and its associated plant is to maximize the turbine work cycle by producing and maintaining the lowest economic heat rejection pressure and temperature at the turbine exhaust e.g.: If the heat reject at 40℃:



The use of condenser increases the specific work output of turbine from $(h_1 - h_3)$ *to* $(h_1 - h_2)$

Figure (2.1) Condenser pressure VS turbine output power

The figure above shows the increase in work obtained by fitting a condenser to a noncondensing unit, the thermal efficiency of a condensing unit therefore is higher than that of noncondensing unit for the same available steam. [2][3][9]

2-To recover high quality feed-water in the form of condensate and feed it back to the boiler without any further treatment. [2][3][9]

3- The design of the condenser also provides a net positive suction head for the condensate extraction pumps and facilitates the removal of air and other non-condensable gases from the turbine exhaust steam. [9]

2.1.2 Types of condensers:

Mainly steam condensers are two types:

1-surface condenser.

2-jet condenser (direct contact).   [At all]

2.1.2.1 Surface condenser:

It's the most common type that used in power plants. They are shell and tube heat exchanger, where the two fluids do not come in direct contact, and the heat released by the condensation of the steam is transferred through the walls of the tubes into the cooling water continuously circulating inside them. [10]

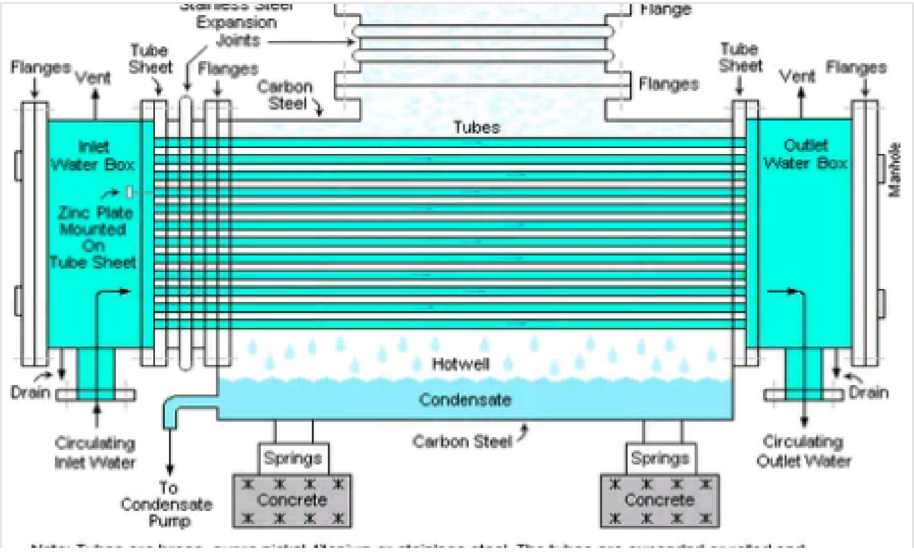


Figure (2.2) Surface condenser

Classification of surface condenser:

1- Depending upon the position of condensate extraction pump, flow of condensate and arrangement of tubes:

I-Down flow condenser.

II- Central flow condenser.

2-depending upon number of cooling water passes:

Single-pass, double-pass, or 3 or 4-passes.

-In single pass water inter from one side of condenser and flows once through all the tubes in parallel and leaves through the second one. [4][5]

-Uses where is a large cooling water supply.

-requires twice as much water flow, but results in half the water temperature rise and thus lower condenser pressure.

-Also it’s good for plant for plant thermal efficiency, and reduce thermal pollution. [4]

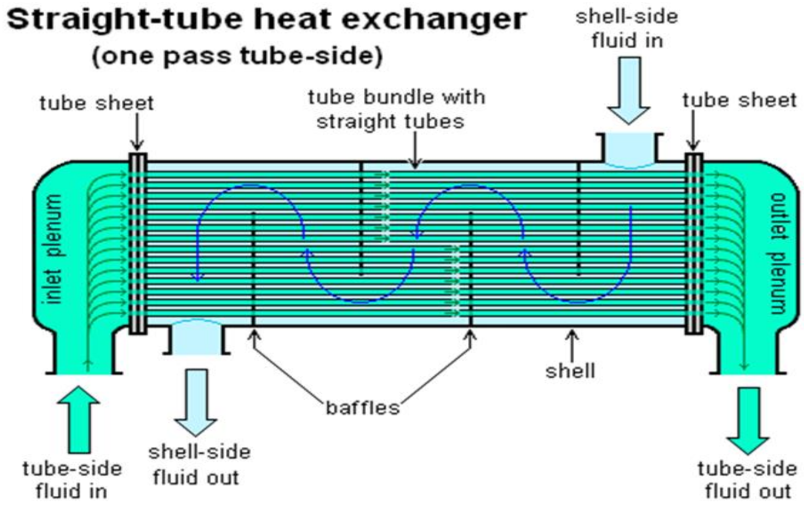


Figure (2.3) one pass tube side

-In two pass, water enters half the tubes at one end of a divided inlet water box, passes through these tubes to an undivided water box at the other end, reverses direction, and passes through the other half of the tubes back to the other side of the divided water box.

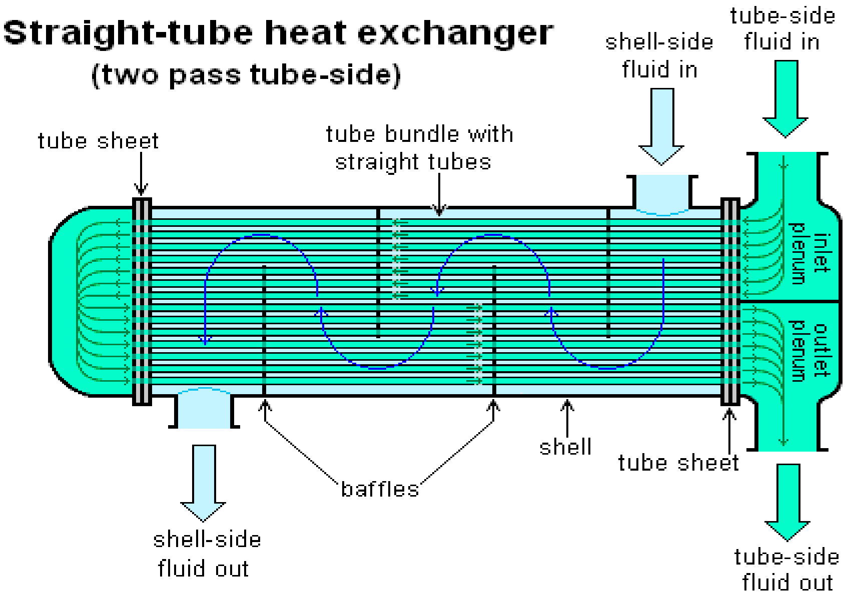


Figure 2.4 Two Pass Tube side

3-The number of compartments, usually one compartment for each set of turbine two-flow exhausts. [8]

4-Orientation of the condenser tubes, transverse or parallel to the axis of the turbine. [8]

2.1.3 Design Layout of Condenser:

Condenser main parts are illustrated in Figure (2.5)

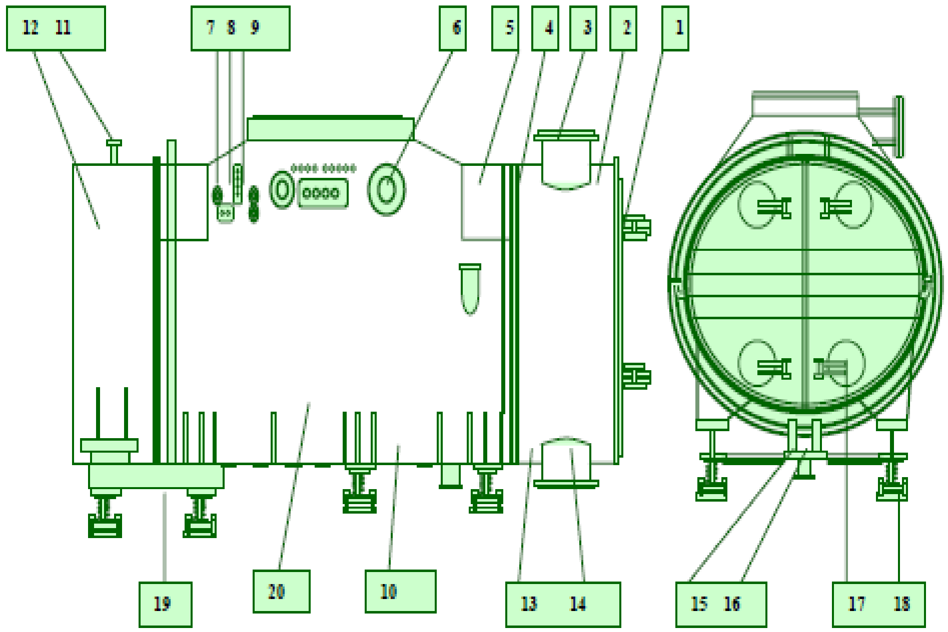


Figure (2.5) surface condenser layout

Table (2.1) Surface condenser components

Item	Name	Item	Name
1	waterbox end door	11	Air release
2	waterbox	12	Return waterbox
3	C.W outlet	13	Belows support beam
4	Tube plate	14	Waterbox drain
5	Level control connection	15	C.W inlet
6	Flash box vent	16	Atmospheric exhaust drain
7	Heater vent connector	17	Extraction pump suction
8	Recirculation connector	18	Inspection door
9	Dearator vent	19	Spring mounting
10	Hot well	20	Condenser shell

2.1.3.1 Tube bundle:

The condenser tubes are made of aluminum brass. The ends of each tube are secured in the tube plates by expanding the end in the parallel fashion and the inlet ends are bell-mouthed to improve the water flow. Between the tubes plates the tubes are supported by sagging plates arranged so that each tube is slightly higher at its center than its end. This creates a slope towards each tube plate which ensure total drainage of the tubes when necessary. It is divided into two tube bundles into which steam can flow from all sides. The bundles are designed to obtain a low condenser pressure along with a good deaeration and no sub-cooling of the condensate.

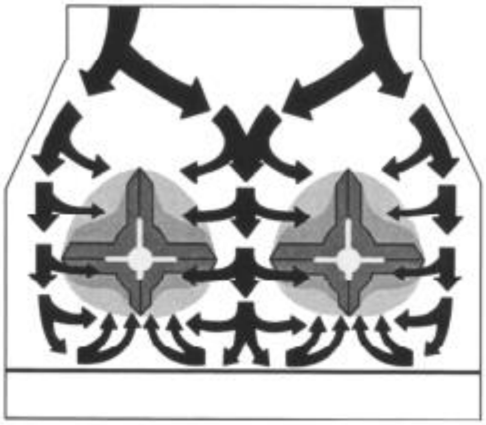


Figure (2.6) tube bundle

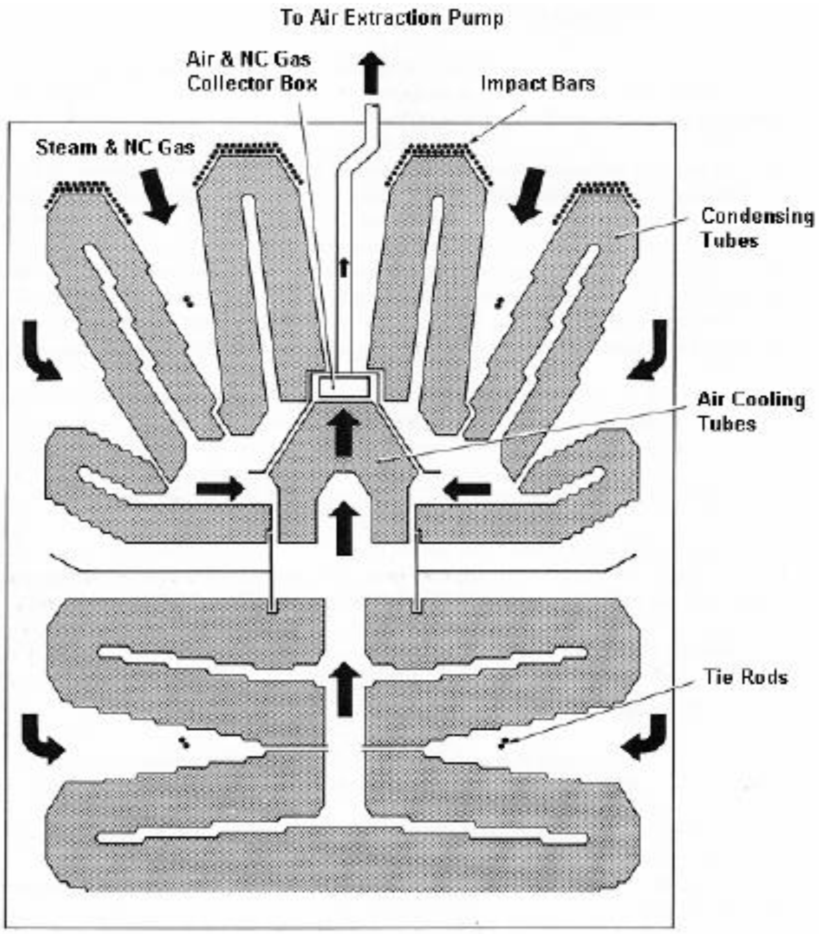


Figure (2.7) tube bundle and air cooler

2.1.3 Internal component of the surface condenser:

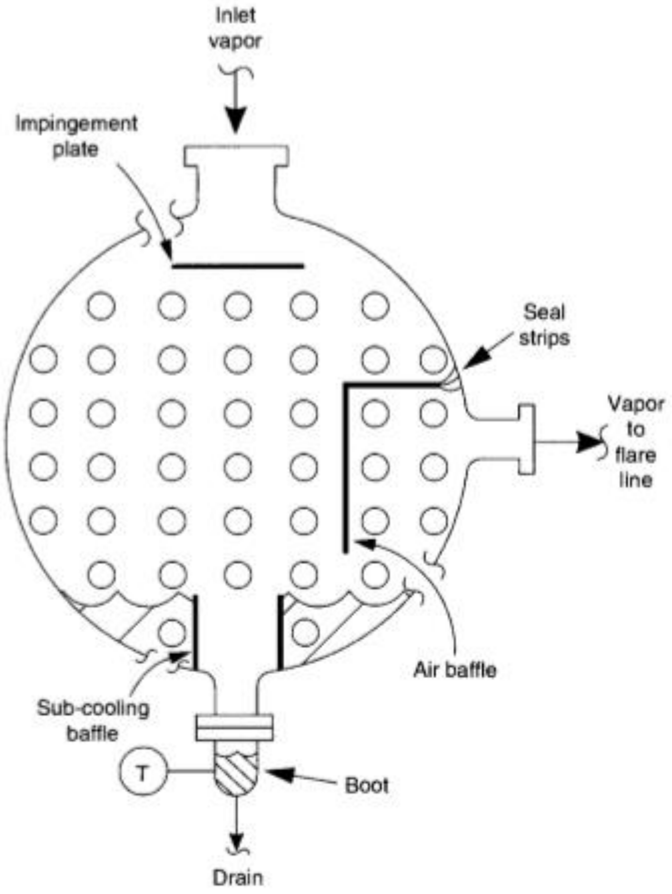


Figure (2.8) internal components of surface condenser

1**impingement plate** is specified to distribute the fluid, induced erosion, cavitation and induced vibration. [5]

-To protect the tubes from the erosive velocity of the shell-side inlet vapor. [7]

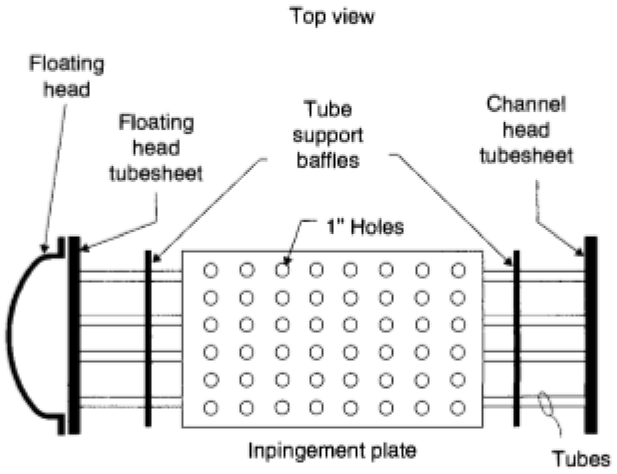


Figure (2.9) Impingement Plate

2**Baffles** are subjected to:

-Direct steam flow.

-distribution steam.

-keep steam away from the air offtake zone.

-also sub-cooling baffles use to prevent sub-cooling condensate from falling in the hot well. [5]

-The air or vapor baffle inside the surface condenser is critical to proper performance of the downstream vacuum ejector or vacuum liquid ring seal pump. [7]

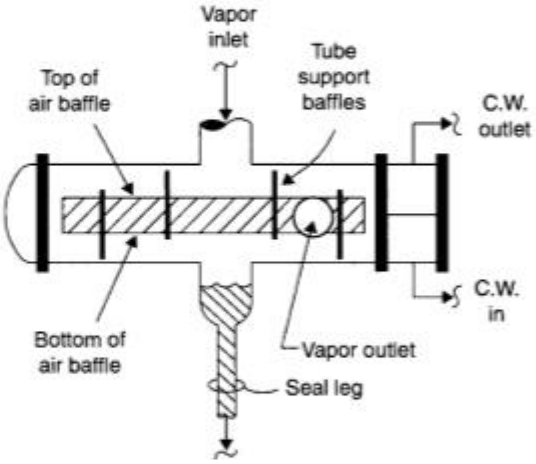


Figure (2.10) air baffles

3\Seal strips:

-Its prevent leakage of hot vapor between the edge of the air baffle and the shell I.D.

-The purpose of these seal strips is to prevent hot vapor in the feed from bypassing 90% of the tubes in the condenser, and overloading the downstream ejector with hot gas and steam

-Most surface condensers are used in steam turbine exhaust service, where copper or bronze type seal strips are the material of choice. [7]

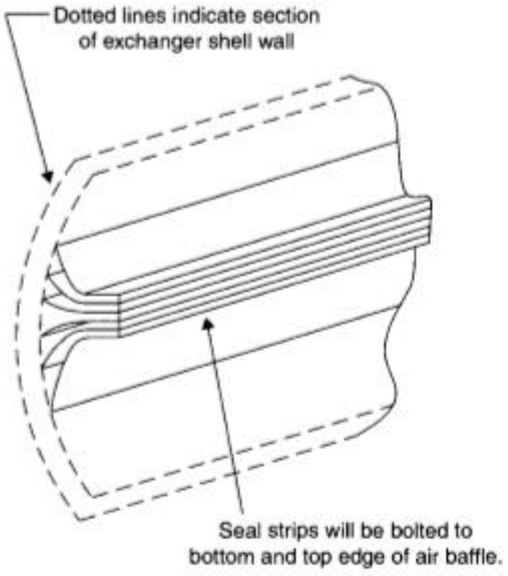


Figure (2.11) Seal strips

4**Hot well**: to collect the condensate steam.

5**condenser tubes**:

-The circulating cooling water moves through it.

- It provide the heat transfer.

-Usually made of Munts metal. [5]

6**supported sheets**:

-Prevent the tubes from sagging between tube sheets.

-also help to partition steam for uniform distribution in the shell. [5]

2.2 Air extraction system:

Air, ammonia and other non-condensable gases, resulting from air in-leakage or the decomposition of water treatment chemicals, are present in the turbine exhaust steam and accumulate in the condenser, and they must be removed from the condenser sell. [9]

In order to maintain the highest possible vacuum, air and non-condensable gases must be removed from the condenser.

The removal of air and the non-condensable gases not only reduced the backpressure, but prevents them from entering the system, thus reducing the possibility of corrosion in the piping and boiler.

To achieve this, we must use certain devices which called vacuum system.

This vacuum system consists two devices which are:

1-Vacuum pump.

2-Steam ejector. [1][2]

2.3 Functions of the Air Extraction System:

The main functions of the condenser air extraction system are to:

1- Extract air, ammonia and other non-condensable gases from the condenser to maintain the condenser vacuum.

2- Prevent air blanketing of condenser tubing that could dramatically reduce the heat transfer and stop the condensing process.

3- Reduce the condensate dissolved oxygen levels that could lead to corrosion of boiler tubing.

4- Prevent condensate ‘sub-cooling’ caused by the presence of air lowering the steam saturation temperature. [9]

2.4 Types of air extraction systems:

2.4.1 Steam Jet Ejector System

The steam jet ejector is a type of vacuum pump with no moving parts and is a relatively low cost component, which is easy to operate and requires little maintenance. In a steam jet ejector, a steam nozzle discharges a high velocity jet across a suction chamber. This jet stream creates a vacuum, which induces air and NC gas into the suction chamber. The air and NC gas are entrained in the steam and expelled out through a diffuser. The diffuser converts the velocity energy into pressure energy, which helps to discharge the mixture against a predetermined backpressure. [11]

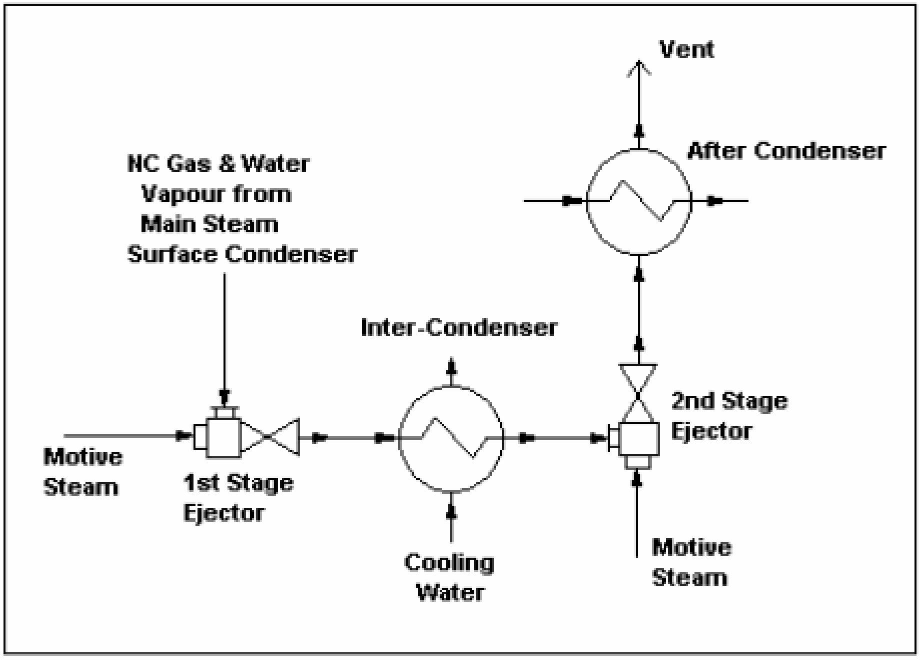


Figure (2.12) SJAE arrangement

The steam jet ejector's dimensions fix its capacity, which limits its throughput, and the practical limits on the compression it can deliver. To achieve greater compression, multistage steam jet ejectors can be used, arranged in series. Condensers are typically used between successive ejectors in a multistage steam jet ejector system, because they reduce the vapor loading to successive ejectors. This allows smaller ejectors to be used and reduces steam consumption. An after-condenser is sometimes used after the final stage, to condense vapors prior to discharge, although this has no effect on performance. [9]

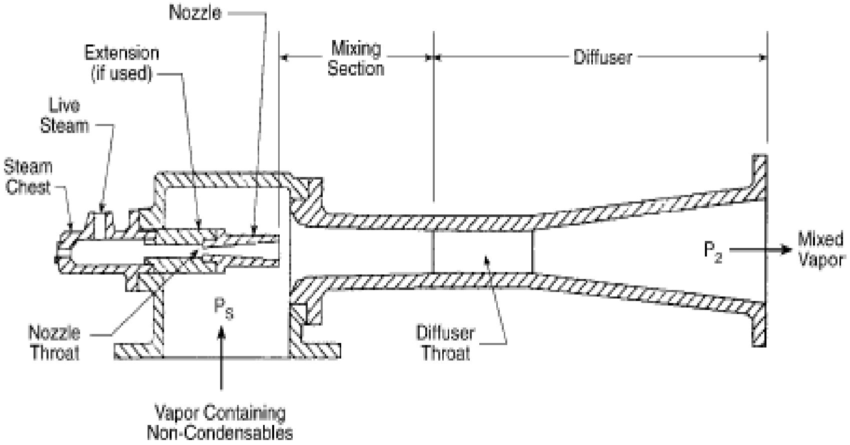


Figure (2.13) Steam jet air ejector (SJAE)

2.4.2 Liquid Ring Vacuum Pump (LRVP) System:

The LRVP consists of an eccentrically mounted multi-vane impeller, rotating in a round casing that is partially filled with seal liquid. The seal liquid is thrown to the outside by centrifugal force and the quantity is such that the impeller vane tips are always immersed. Due to the eccentric mounting of the impeller, the volume enclosed between each pair of impeller blades and the liquid ring varies. Air is drawn into the spaces between the impeller vanes at the inlet port, where the volume is increasing, and is then compressed and discharged through the outlet port where the volume is decreasing. A small portion of seal water is constantly lost with the discharge air and must either be constantly made up or recirculated from a seal water separator vessel.

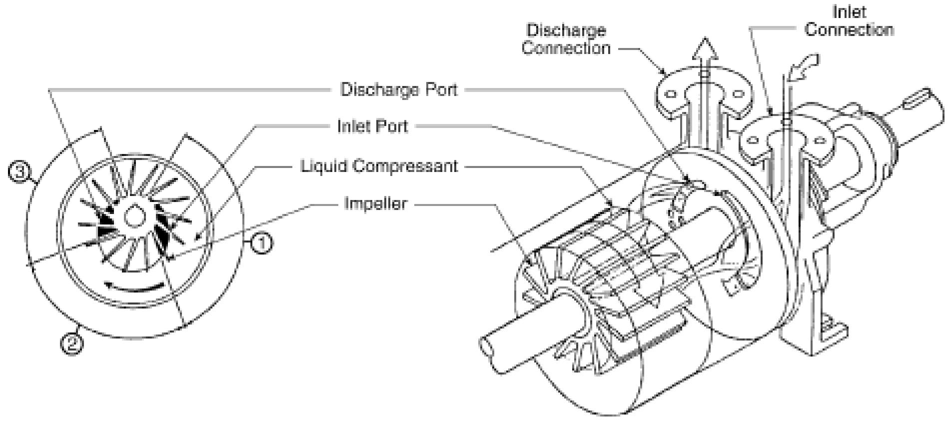


Figure (2.14) liquid ring vacuum pump (LRVP)

A LRVP may have either a single or multi-stage impeller and it is the vapor pressure of the seal liquid that limits the maximum vacuum obtainable. As the seal liquid absorbs the heat generated by compression and friction, it generally requires cooling to keep it below its saturation temperature. If the seal liquid is allowed to heat up and vaporize, it will take up impeller space and reduce the capacity of the LRVP. If this is allowed to continue, cavitation will occur inside the LRVP, resulting in damage to internal surfaces. To prevent cavitation, the operating vacuum must be limited to 0.85 kPa above the vapor pressure of the seal liquid. [14]

LRVP’s are positive displacement by nature and if there is insufficient suction load, the suction pressure can fall to the vapor pressure of the seal liquid, causing destructive cavitation to occur.

Some modern LRVP also spray the seal water into the suction line to sub-cool and condense any incoming steam vapor, which reduces the incoming suction volume and increases the LRVP’s capacity. [12]

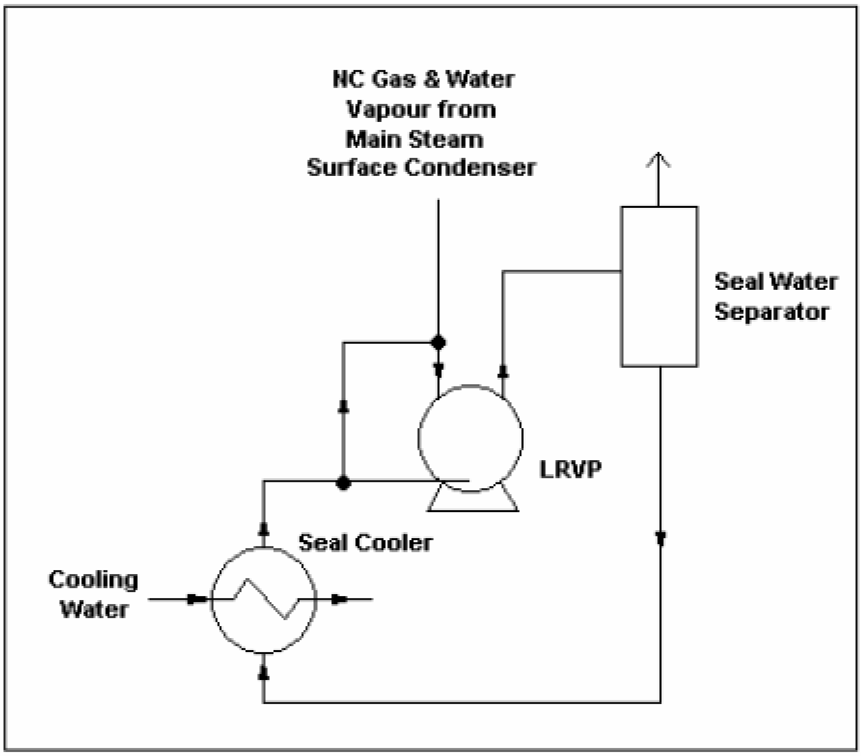


Figure (2.15) LRVP System Arrangement

2.4.3 Air Ejector and LRVP System

The air ejector is similar in nature to the steam jet ejector except that it uses atmospheric air as its motive fluid. This air is usually driven by the action of a liquid ring vacuum pump connected to the air-operated ejector as part of an overall system.

The advantage of this system is that it raises the LRVP suction pressure so that the LRVP is not prone to cavitation, the system can obtain higher suction vacuums and does not require a steam source. [13]

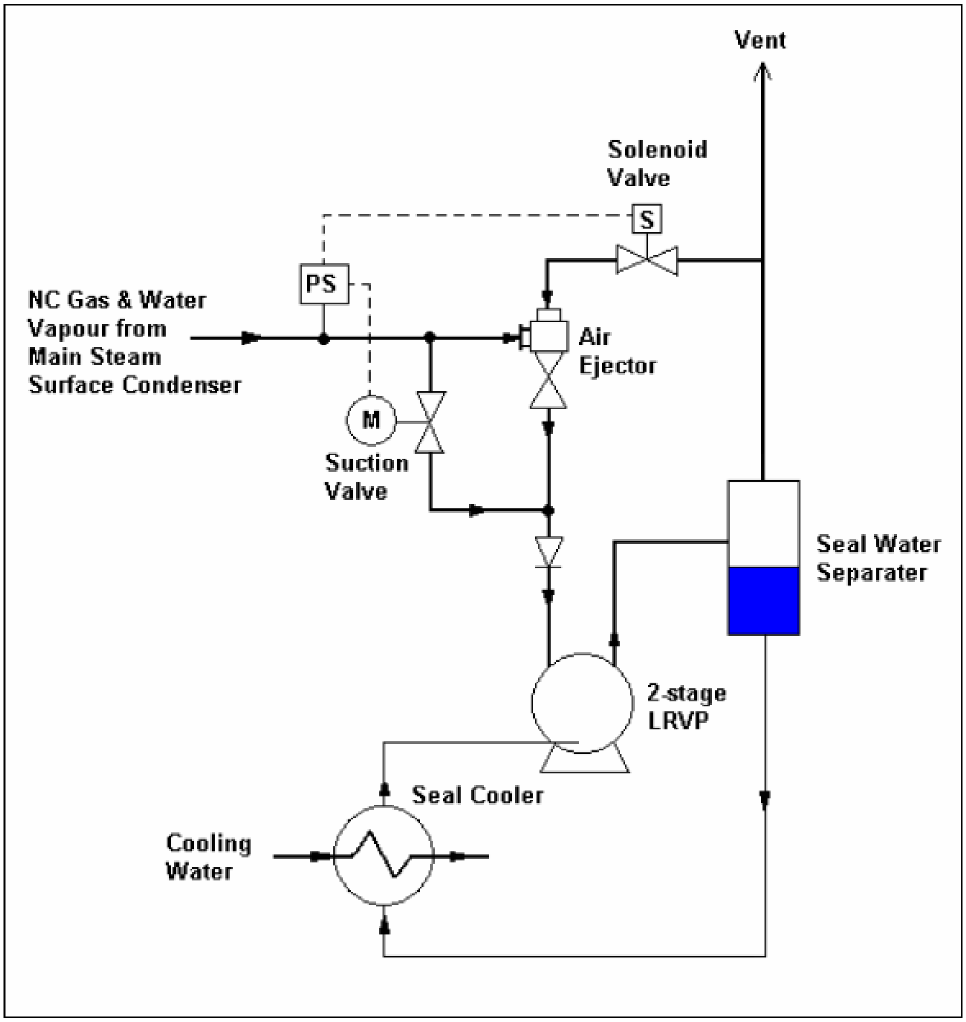


Figure (2.16) Air Ejector and LRVP System

2.5 Condenser and back pressure:

To illustrate the important contribution made to the work done by operating at a vacuum, consider Figure (2.17). Steam is admitted to a turbine at a pressure of 11 bar absolute as shown by *Pi*. The volume of the steam is 0.177 m3/kg. If, after expansion in the turbine, it is rejected at a pressure *Pi* of 1 bar absolute the volume will have become 1.7 m^3/kg and the work done will be represented by the area under the curve between the limits shown by Pi and P2.

If, now, the final pressure is reduced to 0.5 bar absolute the expansion will continue to point, where the volume is 3.3 m^3/kg. Thus, the extra work obtained per kilogram of steam is represented by the shaded area. This is a considerable amount of extra work, obtained by improving the back pressure by 0.5 bar. To achieve a comparable amount of extra work at the inlet to the turbine the steam pressure would have to be lifted from *Pl* to P4, i.e. from 11 to 17.5 bars as shown by the cross-hatched area.

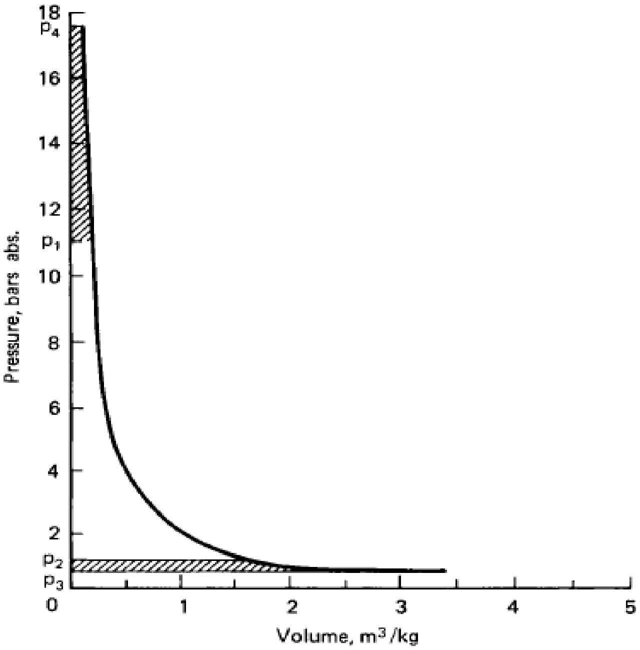


Figure (2.17) pressure vs volume

It is easy to see that even small changes in back pressure can cause considerable changes in the work done per kilogram of steam.

So it is easy to see why turbine back pressure is the most important terminal condition of all.

Therefore it is important to the efficient operation of a unit that its back pressure is always maintained at the optimum level. [15]

2.6 **Influence of back pressure on the turbine output power:**

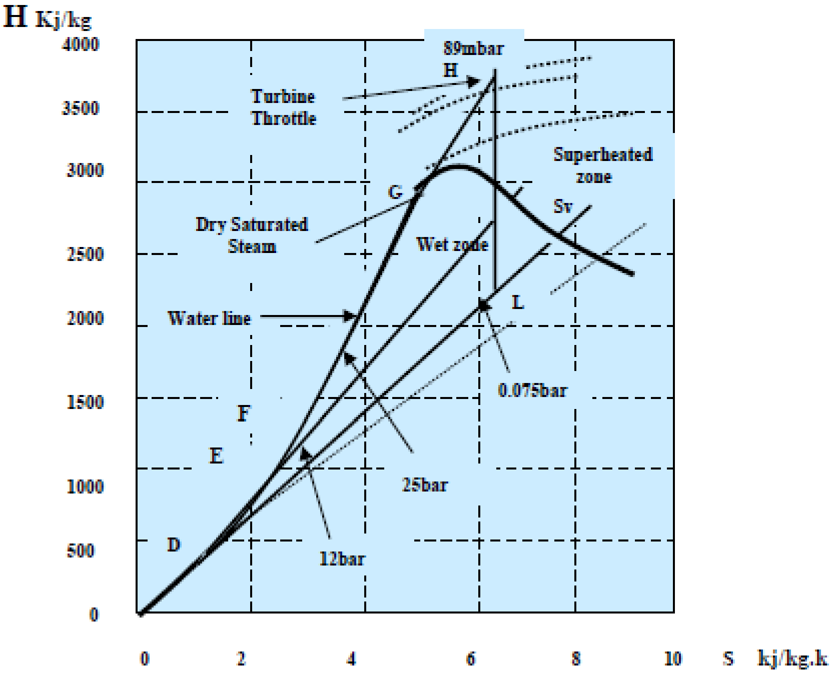


Figure (2.18) Steam cycle on the Moller diagram

Turbine backpressure is the pressure at the turbine/condenser flange. [8]

From Moller diagram, it will be clear that a rise in back pressure from 0.075 bar to 0.16 bar will cause a rise in the enthalpy of the exhaust above that of point L, and thus reducing the amount of heat which can be converted to power. [9]

There can be several possible causes for the backpressure to rise, among them:
- An increase in circulating water inlet temperature.
- A reduction in circulating water flow.
- Fouling of the inside or outside surfaces of the condenser tubes.
- An increase in concentration of non-condensable gases in the shell side.
- A degradation of the air-removal exhauster. [8]

2.7 Effect of varying the back pressure on the whole unit:

From what has already been said it follows that a large amount of extra work is done by the steam when the back pressure is reduced. If this were the whole story then lowering the back pressure would always result in increased output from a unit. The trouble is that as the back pressure improves certain losses increase. These are mainly:

1-increasing CW pumping power.
2-increasing Leaving loss.
3 Reducing condensate temperature.
4-increasing Wetness of the steam. [15]

2.8 Parameters that affect the backpressure

2.8.1 Effect of CW temperature:

First, calculate the drop in CW inlet temperature from the optimum value. At given backpressure, saturation temperature and initial temperature difference, and determine the initial factor F1from figure (3-19). Then:

The new saturation temperature = $F_1\theta_1$+New CW inlet temperature.

Where θ_1 = initial temperature difference (design value)

Then determine the equivalent saturation pressure.

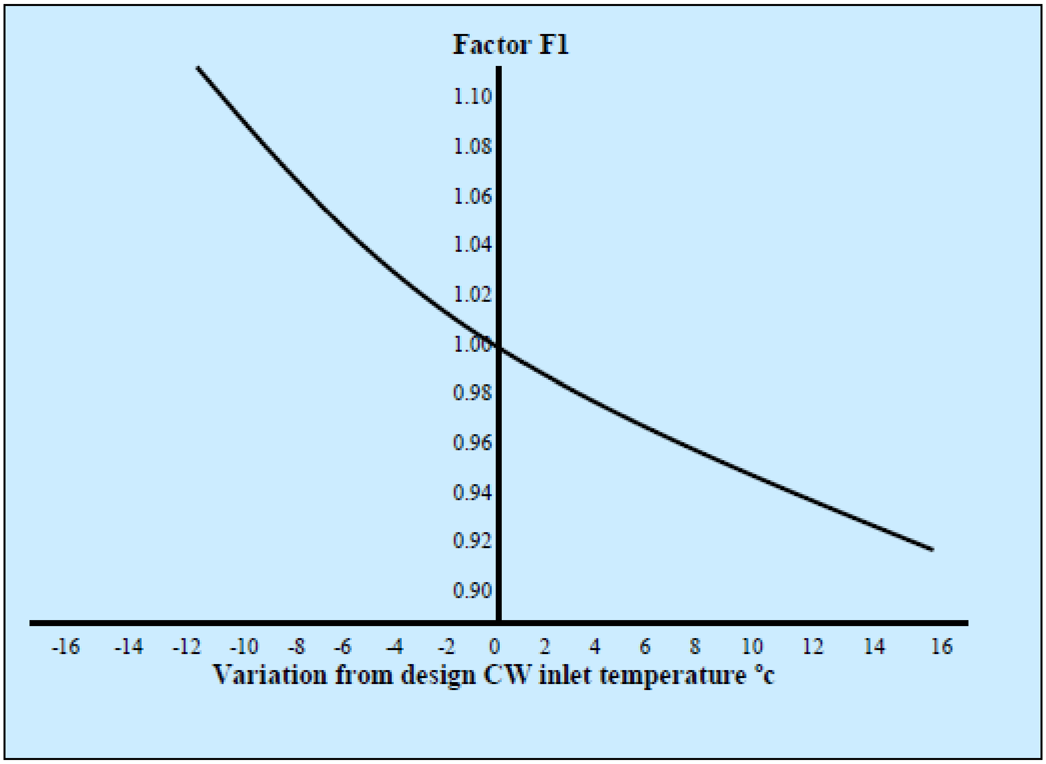


Figure (2.19) Effect of CW inlet temperature

The cooling water inlet temperature should be sufficiently low to have a good vacuum in the condenser shell. It's usually recommended that Δt_i, should lie between11 to 17℃ , and TTD should not be less than 3℃. [1]

2.8.2 Effect of CW flow:

The new saturation temperature =$F_2 \theta_1$+New CW inlet temperature. [16]

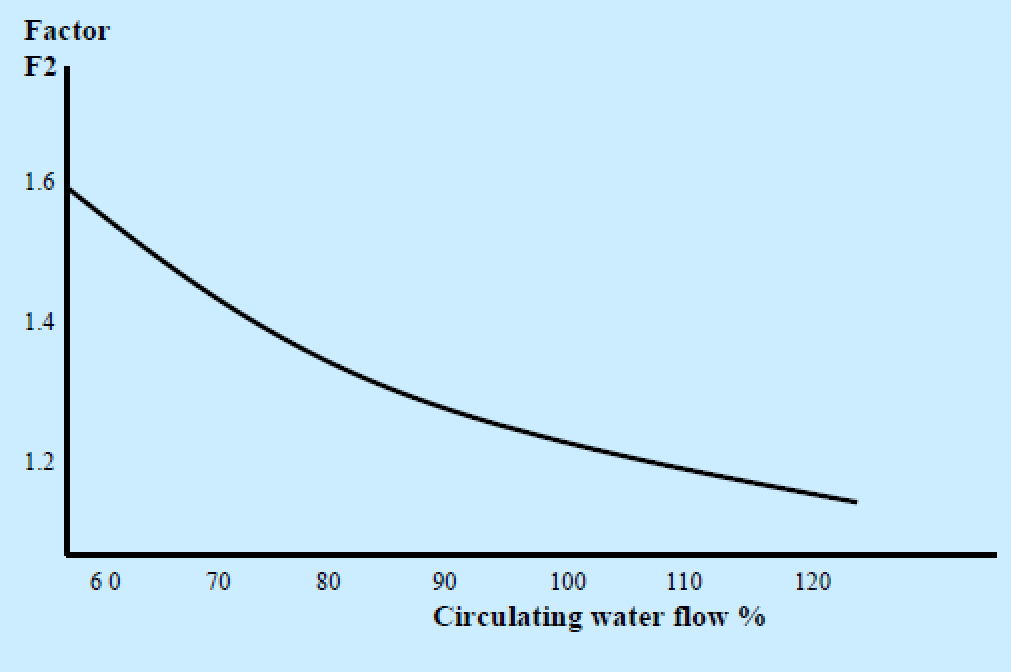


Figure (2.20) Effect of CW flow

2.8.3 Steam flow to the condenser

The new saturation temperature = $F_3 \theta_1$+ New CW inlet temperature.

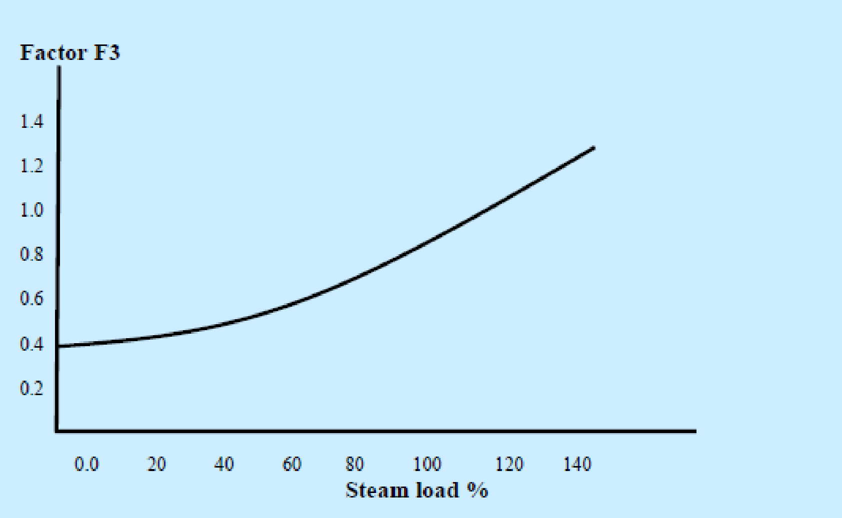


Figure (2.21) Effect of steam flow

Then the combined effect of all three changes (CW temperature, CW flow and steam load) is:

The new saturation temperature =$F_1 F_2 F_3 \theta_1$ +New CW inlet temperature.

From saturation temperature, we can find the corresponding backpressure. [16]

2.8.4 Tube fouling:

The surfaces in condensers are not bare metal but are always covered with a certain coat of dirt and corrosion residue. This layer influences the heat transfer and must be taken into consideration.

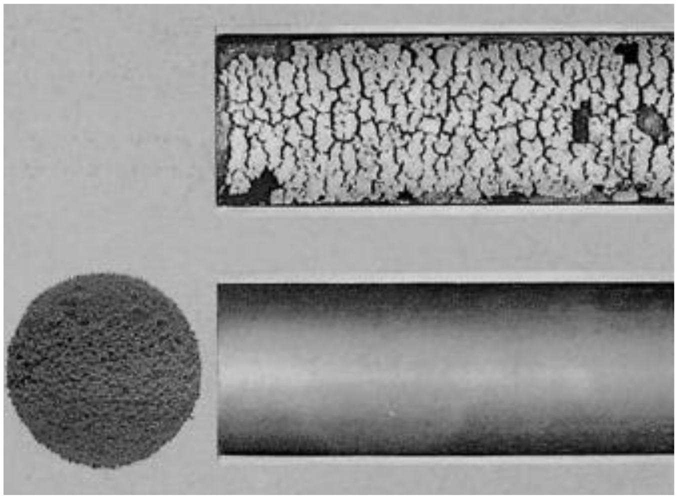


Figure (2.22) Tube fouling

Types of fouling are divided into six distinct categories the most common types are: Crystallization, which occurs in many process streams and cooling tower water. Sedimentation, which is caused by deposits of particulate matter such as clay, sand or rust. Polymerization, which is caused by the build-up of organic products and polymers. Coking occurs on high-temperature surfaces and is due to hydrocarbon deposits. Fouling due to coking is of no significance, since the unit cannot be used at high temperatures. [8]

2.8.5 Tube cleanliness:

It is the ratio of the average heat transfer coefficient of tubes in the condenser to that of a new, acid cleaned tube. It is a very important parameter of condenser performance.

The value of cleanliness factor can be determined at the off load state, here about one of every 200 tubes should be withdrawn from the condenser to give a good representation of the operating conditions.

Then the thermal resistance of the sample tubes is measured and compared with the thermal resistance of some of tubes after cleaning. [8]

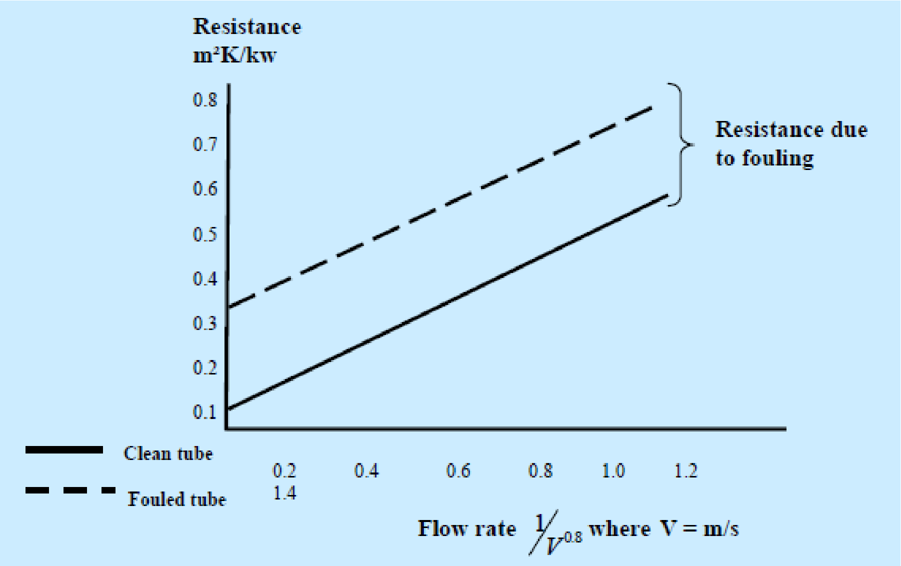


Figure (2.23) Effect of tube fouling

2.8.6 Effects of Air and NC Gases on the Condenser:

If the condenser pressure is assumed to be constant throughout, then the partial air pressure must have increased and the partial steam pressure fallen (when compared to the turbine exhaust steam). This lower steam vapor pressure leads to a lower saturation temperature. As the condensate in the 'hot well' is in contact with this steam vapor its temperature can fall due to heat transfer and this can result in sub-cooling.

Sub-cooling of condensate and dissolved oxygen pickup can also occur as the condensate falls through localized, accumulated air pockets within the condenser. [9]

Other significant effects of air and non-condensable gases on the condenser is that they can 'blanket' the condenser tubes and greatly reduce the heat transfer, which leads to a loss of vacuum and a corresponding rise in the steam saturation temperature resulting in reduced turbine work output.

This reduction in the rate of heat transfer by ‘blanketing’ can be significant and if left unchecked could stop the condensing process altogether.

Another effect of air build-up in the condenser is it can lead to high condensate dissolved oxygen levels. If left unchecked this can lead to increased boiler tube corrosion. Likewise, a build-up of ammonia vapor pockets within the condenser can lead to corrosion attack on the copper within the condenser tubes, which can lead to leaks and contamination of the condensate system by the less than pure circulating water. [9][7]

2.9 Correct Sizing of Air Extraction Systems:

The information needed to accurately size a liquid ring vacuum pump includes:

- Suction pressure
- Suction temperature
- Mass flow rate and the molecular weight of fluid components
- Vapor pressure for each fluid component
- Seal fluid data, if other than water
- Temperature of seal fluid or cooling water
- Discharge pressure [18]

1-The Heat Exchange Institute of the USA (HEI 1995, p.30) specifies that the condenser venting equipment shall be designed for a suction pressure (3.39 kPa abs.) [19]

2- The HEI (1995, p.30) also provides guidance on the venting system design suction temperature:

Suction temperature = steam saturation temperature at 3.39 kPa - 0.25(condenser saturation temperature- circulating water inlet temperature)………… eq. (2.1)

3- Using the previously obtained design suction temperature of, and pressure of 3.39 kPa absolute, the water vapor load from Appendix E. [19]

4- To optimize the capacity of the air extraction system, the design capacity will be based on the HEI maximum recommended air in-leakage rate of 142 liters/min at the condenser design operating pressure of 9.5-kPa absolute. This capacity selection will also reduce the potential for LRVP cavitation developing, as the capacity will be closer to actual air in leakage rates.

This dry air discharge flow needs to be converted to a saturated mass airflow at the LRVP suction and a Dry Air Equivalent (DAE) found. The design air extraction rate at a condenser pressure of 3.39-kPa can be found by using equation:

$$Q_{new} = Q_{knowm} \times \frac{\sqrt{P_{atmosphere} - P_{new}}}{\sqrt{P_{atmosphere} - P_{known}}}$$

……………………….. eq. (2.2)

2.10 Previous studies:

1-Performance Analysis of Surface Condenser under Various Operating Parameters Ajeet Singh Sikarwar, Devendra Dandotiya, Surendra Kumar Agrawal, Jul-Aug 2013

This paper deals with the factors or parameters which reduced the efficiency of the condenser.

This paper evaluated all the aspects of condenser which affecting the performance of power plant. This paper worked on three causes which affecting the performance of condenser are deviation due to inlet temperature of cold water is 25.4mbar, deviation due to cold water flow and load 0.8mbar, deviation due to air ingress/dirty tube, so total deviation of pressure in the condenser is 35.4mbar. Eventually, this paper finds that the total efficiency of a power plant will reduces to 0.4% by all these deviations in the condenser and by overcome these three reasons, the performance of power plant can be rises with a good level.

2-Parametric Analysis of Surface Condenser for Thermal Power Plant

Vikram Haldkar, Abhay Kumar Sharma, R.K. Ranjan, and V.K. Bajpai, Dec 2013

This paper deals with the factors or parameters which reduced the efficiency of the condenser and power plant.

In this paper, causes which effecting the performance of condenser are deviation due to cooling water inlet temperature, deviation due to water flow rate and deviation due to condenser pressure in energy efficiency of plant is consider. Eventually this paper find the total efficiency of a power plant will reduce 2.7% by all these deviations in the condenser and by overcome these three reasons, the performance of power plant can be rises with a good level.

This paper investigate the effect of steam velocity, the axial variation of heat transfers along condenser tubes, the effects of air or other non-condensable gas concentration and the interaction of these various phenomena were studied not only with regard to heat transfer but also flow resistance and pressure drop.

Point of agreement both of these studies finding that using vacuum system affect by the operation and the ambient conditions.

3-The effect of condenser backpressure on station thermal efficiency: Grootvlei Power Station as a case study:

KM van Rooyen, November 2014

The main contributory factor to the thermal efficiency losses was identified to be the condenser backpressure losses that the station was experiencing. This loss was responsible for approximately 17% of the total efficiency losses.

The deliverables were to determine the cause of the condenser backpressure loss and propose possible resolution.

Point of agreement that variation in the backpressure affect the thermal efficiency. And it’s a critical condition.

Chapter Three

Methodology

3. Collecting and presentation data:

3.1 Basic over view of Khartoum North power Station:

Khartoum north power Station was first construction of two unit of 30MW whine –generator with two water- wall boiler **PH 1** (**phase 1)**1989.In 1994 there were other two unit 60MW turbine –generator unit with two water-wall boiler PH2 (phase 2). After this station was under construction (for **PH3 (phase 3**)100MW turbine –generator unit with two water –wall boiler) in 2006 and ended in 2010 because rising power demand in Sudan.

Figure (3.1) Basic over view of (KNPS)

3.1.1 Basic layout of the power station:

Most of Sudan electricity comes from hydraulic power stations .The following is a basic description of electricity generation process that takes at Khartoum north power station:

Fuel oil is obtained from road tracks or rail way and delivered to the large tanks .from the fuel oil tanks it is pump by forwarding pumps and heated to be burn in boiler .this is done with the aid of primary air which is heated .

The fuel oil is burnt and the energy that is given off is used to heat demineralized water in an array of boiler tubes .this generator high pressure steam which drive a turbine .The unwanted gases formed from the combustion process are sent to smoke stack where it released into atmosphere .the thermal energy is converted into mechanical energy by steam turbine .A generator is coupled to the turbine shaft and convert energy into electrical energy .From here the generator produces an AC voltage which is stepped up by the transformer to high voltage to minimize transmission losses and then transfer to the grid .here after it is transferred to the substation and lastly to consumers .

For the purpose of this research, the focus will be mainly on the condenser area at power station both **phase1, and phase 2** are using a steam air-ejector**, PH3 is** using liquid ring vacuum pumps.

Because **PH1 and PH2** are the same equipment for the vacuum system the study will be only **in PH2** and the new system **in PH3.**

3.2 Vacuum system used in PH2:

Very simply an ejector is a pumping device .it has no moving parts. Instead, it uses fluid or gas a motive force. Very often, the motive fluid is steam and the device is called a" steam jet ejector "Basic ejector components are the steam chest, nozzle, suction, throat, diffuser and the discharge [6].

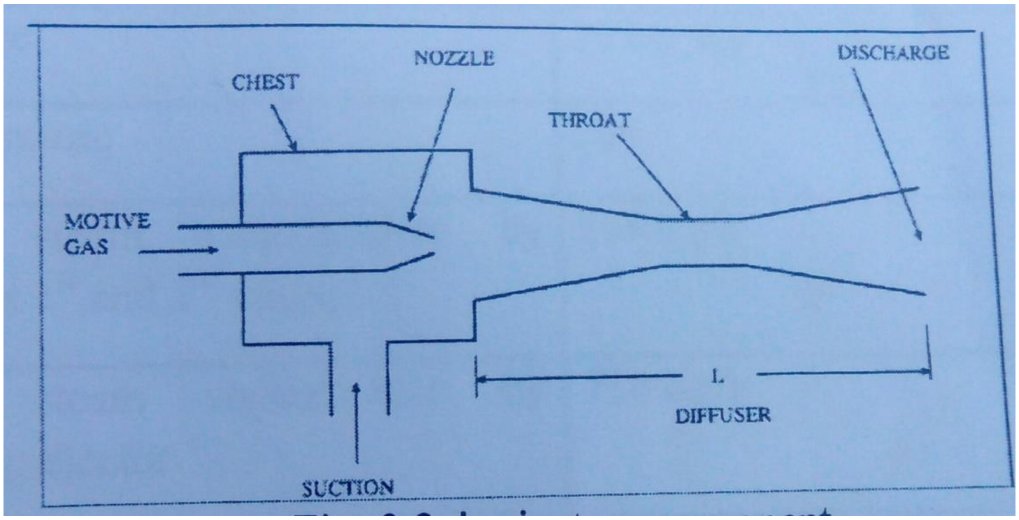


Figure (3.2) Steam jet at ph2

3.2.1 Steam air- ejector Operating Principle:

In the first stage steam –operated air ejector acts as a pump to draw in the air and vapor's from the condenser .the mixture then passes into a condensing unit which Is circulated by feed water .the feed water is heated and the steam and gases are mostly condensed .

The condensed vapors and steam are returned to the main condenser via a drain and the remaining air and gasses to the second stage where the process is repeated.

Any remaining air and gasses are released to atmosphere via a vacuum –retaining valve.

A pair of ejector is fitted to each stage, although only one of each is required for satisfactory operation of the unit.

3.2.2 Operating characteristics and General design data

Table (3-1) Operating characteristics and design data [18]

Suction for main air ejector	
Dry air flow	20Kg/h
Total air vapor mixture	65Kg/h
Suction pressure	60mbar
Discharge pressure	Atmosphere
Steam condition	
Pressure	20 bar abs
Temperature	**230** ℃
Total steam condition by ejectors **1** and **2** stages	203Kg/h
Total steam consumption by hogging ejector	750Kg/h
Cooling water	
Nature	Condensate
Maximum flow	35Kg/h
Minimum flow	20Kg/h
Water pressure on condenser inlet	5bar eff (calculation 18br)
Pressure drop	0.2bar
Suction for hogging air ejector	
Volume to be drained out	**130**$\boldsymbol{m}^3$
Residual pressure to obtain in15minutes	200 mbar abs
Ejector	
1 stage type	8L
2 stage type	3L
Hogging type	6
Condenser	
Condenser **1** stage heat exchange area	6.8m^2

Condenser **2** stage heat exchange area	2.78m^2
Exterior diameter of tubes	19mm
Thickness of tubes	1.65mm(16BGW)
Length of tubes	1.525mm
Number of tubes (**1** stage)	76
Number of tubes (**2** stage)	31
Main material	
Ejector body	Carbon steel
Ejector nozzles	S.S 316L
Condenser body	Carbon steel
Tube bundle	S.S 16L
Design condition	
Ejector designer pressure	25/vacuum bar g
Condenser designer pressure steam side	20 bar g
Condenser designer pressure water side	18 bar g
Silencer	
Flow dry air	66Kg/h at 200mbar abs or 235 at atmosphere
Flow stem	750Kg/h
Flowing back pressure	Atmosphere
Temperature	**200**°C max
Diameter of silence	250mm
Length	1700mm
Weight	90Kg
Body	Carbon steel
Noise absorber	Mineral wall
Protection of noise absorber	Glass material

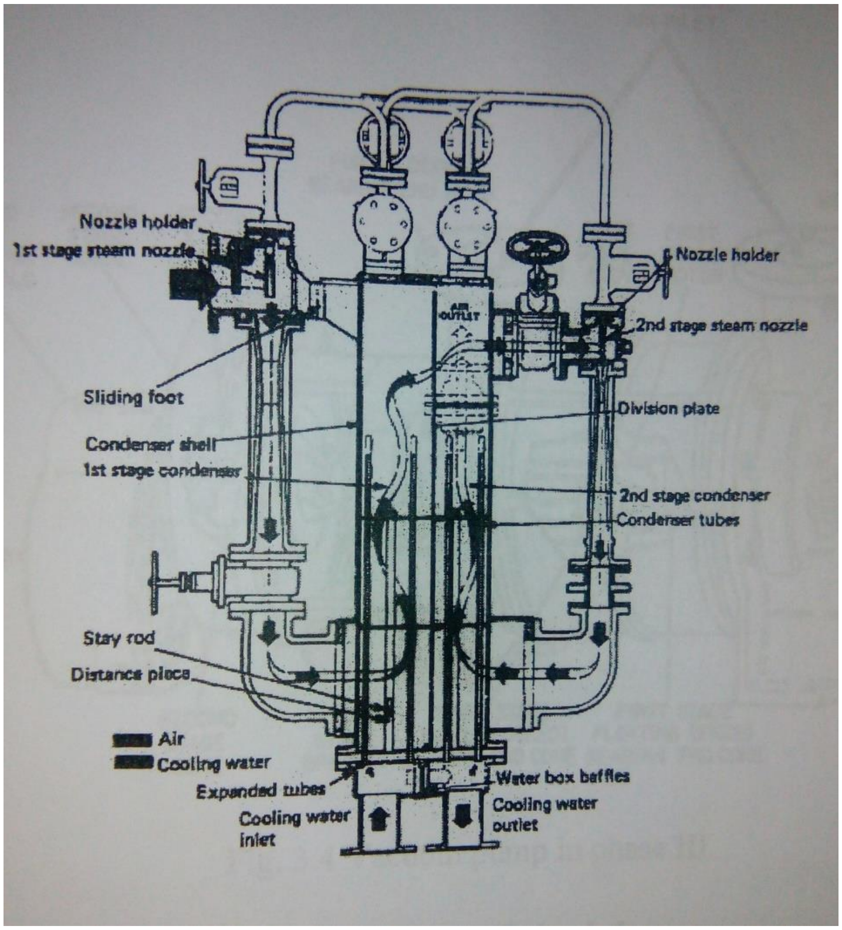


Figure (3.3) SJAE multi-stages

3.3 Vacuum system used in PH3

The main component of the vacuum pump are an electric drive motor is direct couple to a pump drive shaft that is common to both stages of the two stage vacuum pump. Rotors in each stage are rigidly mounted to the shaft and rotate at the same speed as these shafts.

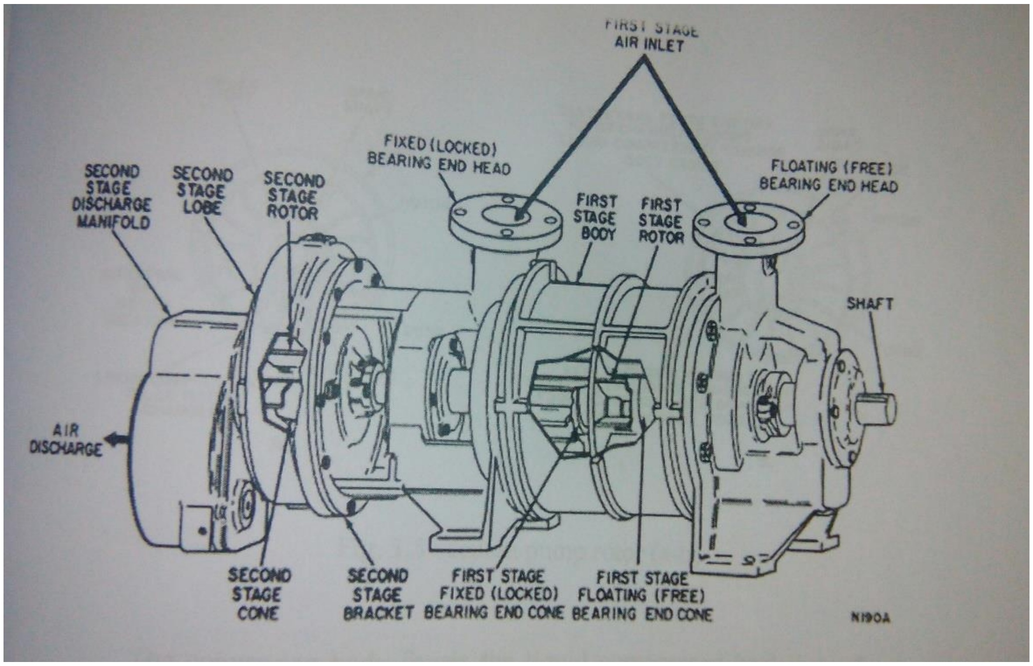


Figure (3.4) vacuum pump at PH3

3.3.1 Vacuum operating principle:

The operating principle of the vacuum pump. Which of the liquid ring type are shown in fig. **(3-5A)**. A rotor revolves without metal contact in a circular body that contains a liquid compressed. The rotor is a casting consist of, serious of blades that project from a hollow cylindrical hub through which the shaft is pressed. These blades are shrouded at the sides form a serious chambers. The curvature of the blades is in the direction of rotation. The body is offset from the centerline of the Shaft.

Starting in **fig (3-5A)**.the rotor chambers are filled with liquid compressed. The liquid compressed is rotates with the rotor. But follow.

The contour of the body. The liquid compressed recedes into the body as the rotor advances as shown in view **B** and empties the rotor chamber **.[6]**

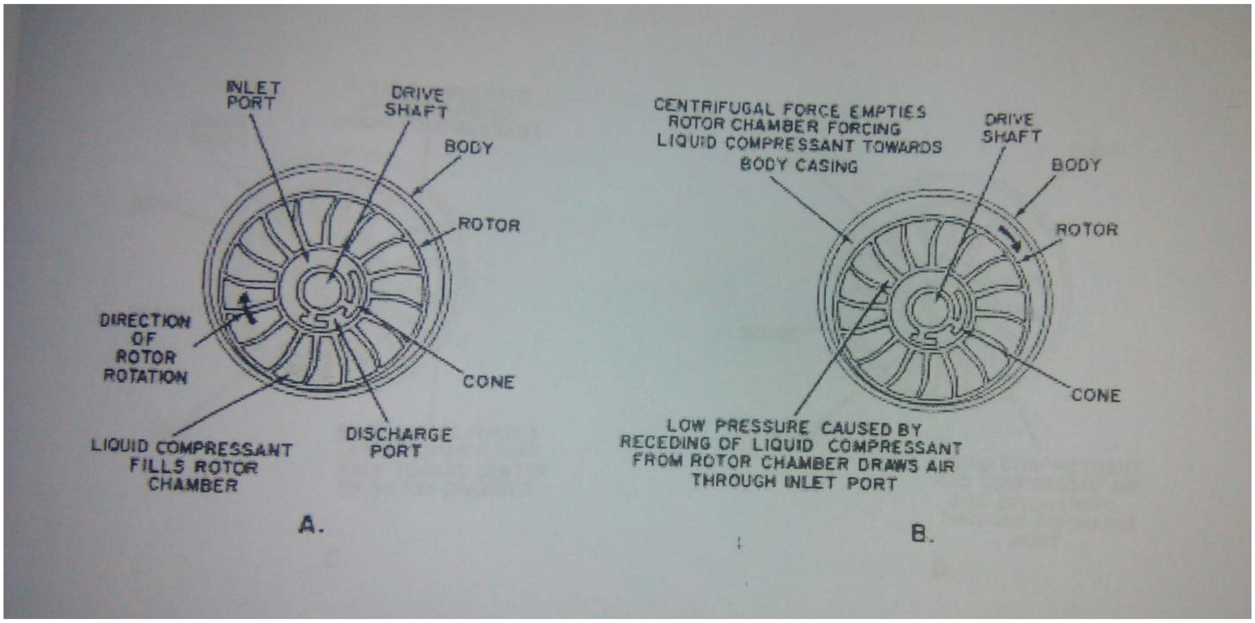


Figure (3.5) vacuum pump rotor

The converging body forces the liquid compressed back into the rotor, chamber as shown in **fig. (3-6c**) ‘until the rotor chamber is full again

This cycle occurs once during each revolution of the rotor. As the liquid compressed recedes from the rotor chamber in fig**. (3-5B**).

The liquid compressed is replaced by air drown through an inlet port in the stationary cone that connects to the pump inlet. As the rotor turns through 360degrees and liquid compressed is force by the body back into the rotor chamber, the air that has, filled the chamber is forced through discharge ports of the cone to the pump discharge is shown in fig. **(3-6D).**

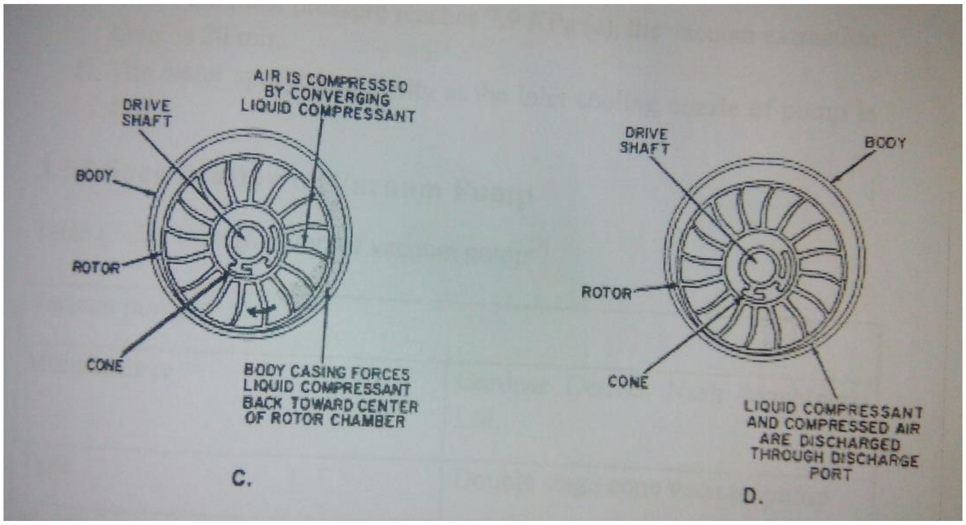


Figure (3.6) vacuum pump rotor

3.3.2 Technical Parameters of the Vacuum pump

- The lowest suction pressure of water –ring vacuum pump: 3.3Kpa.
- Rotating speed of vacuum pump: 740rpm
- Nominal diameter of impeller: 457rpm.
- Linear velocity of impeller: 17.68rpm.
- Shaft power (Max): 45KW, (Min): 28KW;

Shaft power when the pressure is 7.9KPa (a) 33KW;

Shaft power when the pressure is 11.8Kpa (a) 33.8KW.

- Startup power: 40KW.
- The actual suction capacity of vacuum pump (when the inlet pressure is 7.9Kpa (a) and cooling water temperature of condenser is 29C). 35Kg/h.
- Cooling for pump heat-exchanger.
- The designed pressure of make – up water in separator: 2.8 Mpa (it should satisfy the operation pressure of condensate water. If not, the supplier should supply throttling orifice plate or pressure relief valve)

  The make-up water quantity: 0.5t/h.
- Vacuum extraction time when startup:

  A. When the pressure reaches 33.68Kpathe vacuum extraction time is 8 min.

  B. When the back pressure reaches 7.9Kpa (a), the vacuum extraction time is 20 min.

  C. The water spraying quantity at the inlet cooling nozzle of pump is 4t/h.

3.3.3 Specification of Vacuum pump

Table **(3-2):** Specification of Vacuum pump **[19]**

Vacuum pump	
Manufacturer	Grander Denver Nash Machinery Ltd.
Type	Double stage cone vacuum pump
Model number	AT1006E
Rotating direction (look from driven end)	Clockwise
Bearing seal style	Filling seal
Model of bearing	Rolling bearing

Heat exchanger	
Manufacturer	FUNKE
Type and model	Type FP- 14
Heat exchanging area (m^2)	About 6
Working water flow (m^3/h)	8
Cooling water flow (m^3/h)	16
End difference	2
Pressure drop at cooling water side(Kpa)	50
Motor	
Manufacturer	Beijing Bijie motor
Model	Y 315S-8
Rated power	55
Rated voltage	415
Rotating speed	740
Frequency	50
Startup current	720A
Startup time	7s
Temperature rising with rated load	80K
Rated full-load current	111A
The allowable max. operation temperature of motor bearing	95℃
Insulation degree	F
Weight	900Kg
Cooling way	Fan
Protection degree	IP44
Rotating direction	Clockwise
Steam water separator	
Manufacturer	North pressure vessel
Type of model	Upright type
Size(mm× mm)	500×1200
Driving device of pump	
Type and modeling of coupling	Elastic coupling
Cover material	Carbon steel

3.4 Operation data from the controlling unit at KNPS

Table (3.3) Operation data for Ph3

Data	1\7\2017	28\9\2017	11\10\2017
CW inlet temperature, ℃	34.13	30	32
CW outlet temperature, ℃	40.19	39	40
Back-pressure, mbar	84	176	200
Mass flow rate of steam, kg\s	47.71	82.8	90.28
Mass flow rate of fuel, kg\s	4.5	5.83	6.2
Output power, MW	51.24	74	77
Condensate temperature, ℃	48.41	51	54

Table (3.4) Operation data for Ph2

	21\8\2017	8\2017
CW inlet temperature, ℃	29	27
CW outlet temperature, ℃	35	32
Back-pressure, mbar	80	110
Mass flow rate of steam, kg\s	36	24.8
Mass flow rate of fuel, kg\s	2.8	1.95
Output power, MW	36.5	22
Condensate temperature, ℃	47	50

Chapter Four

Calculation & discussion

4. Calculation, analysis, and discussion:

4.1 Variation of backpressure:

To calculate the deviation of back pressure from the optimum value, we will use fig (2-19), fig (2-20), fig (2-21):

-First initial variation in CW inlet temperature from the design value:

By using data of Ph3 (1\7\2017):

$$\theta = 34.13 - 25 = 9.13℃$$

-Second calculate F1, F2, and F3:

From fig (2-19): F1=0.95

From fig (2-20): F2=1.23

From fig (2-21): F3=0.42

-Third calculate the new saturation temperature:

The new saturation temperature= $F_1F_2F_3\theta_1$+ New CW inlet temperature.

$$=0.95*1.23*0.42*9.13+34.13=38.6℃$$

-Fourth From saturation temperature, we can find the corresponding backpressure:

Then the new back pressure= 68mbar.

-We can see Cleary from the operation data, the indicated back pressure is 84mbar, there is a different from the corresponding value about 16mbar, this deviation occur by fouling of tubes and air ingress inside the condenser shell.

- Air extraction equipment can observe this variation, and keep this different constant at 16mbar.

-Fifth calculate thermal efficiency:

Efficiency = $\frac{net,output\ power}{energy\ added\ in\ boiler}$

Net, output power = 0.9 output power = 0.9*51.24 = 46.116MW.

Energy added in boiler = $\dot{m}_f$*Caloric Value of fuel

=4.5*41.470=186.615MW

Efficiency = $\frac{46.116}{186.615}$ = 24.71 %

By using data of Ph2 (21\8\2017):

$$\theta = 29 - 25 = 4℃$$

-we can see clearly the different on CW inlet temperature between July and August.

-Second calculate F1, F2, and F3:

From fig (2-19): F1=0.97

From fig (2-20): F2=1.23

From fig (2-21): F3=0.56

-Third calculate the new saturation temperature:

The new saturation temperature= $F_1 F_2 F_3 \theta_1$+ New CW inlet temperature.

=0.97*1.23*0.56*4 + 29 =31.67℃

-Fourth From saturation temperature, we can find the corresponding backpressure:

Then the new back pressure= 41.6mbar.

-Fifth calculate thermal efficiency:

Efficiency = $\frac{net,output\ power}{energy\ added\ in\ boiler}$

Net, output power = 0.9 output power = 0.9*36.5 = 32.85MW.

Energy added in boiler = $\dot{m}_f$*Caloric Value of fuel

=2.8*41.470=116.116MW

Efficiency = $\frac{32.85}{116.116}$ = 28.71 %

4.2 Using CPAD program to calculate the thermal efficiency:

1- Because the actual steam cycle of KNPS is very complex, it’s very difficult to draw it on the program. Then it will be reduction to a simple Rankine cycle. By knowing the energy which added on the boiler, and the turbine output power. Then it is be easy to calculate the cycle thermal efficiency.

2- Drawing cycle by CPAD as shown in Fig (4.1), and Fig (4.2) by using the available options (boiler, turbine, pump, condenser).

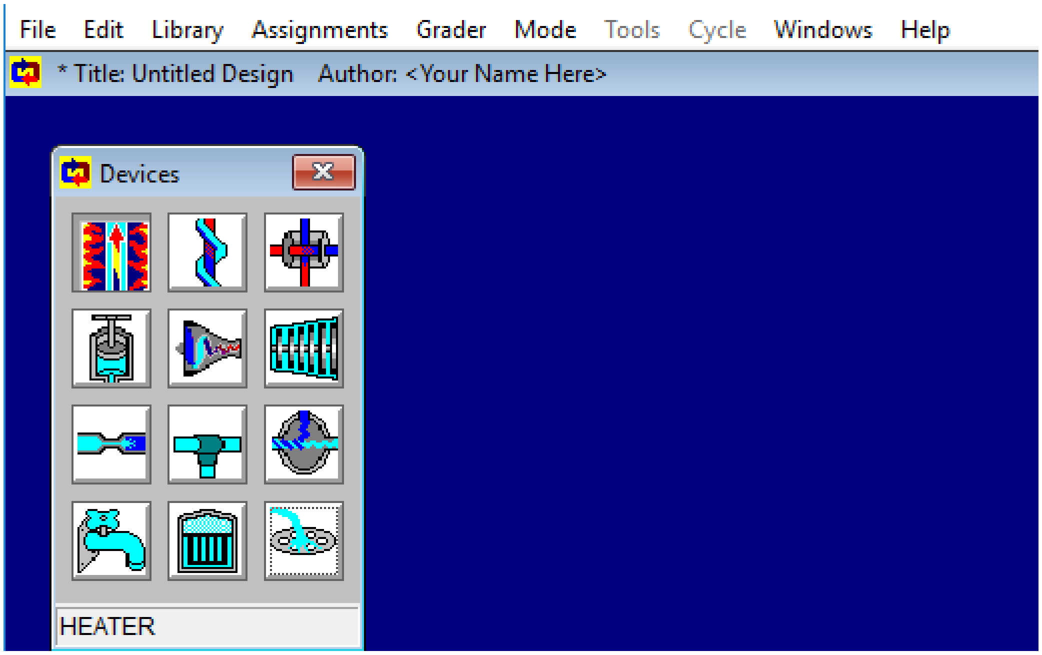


Figure (4.1) CPAD program overview

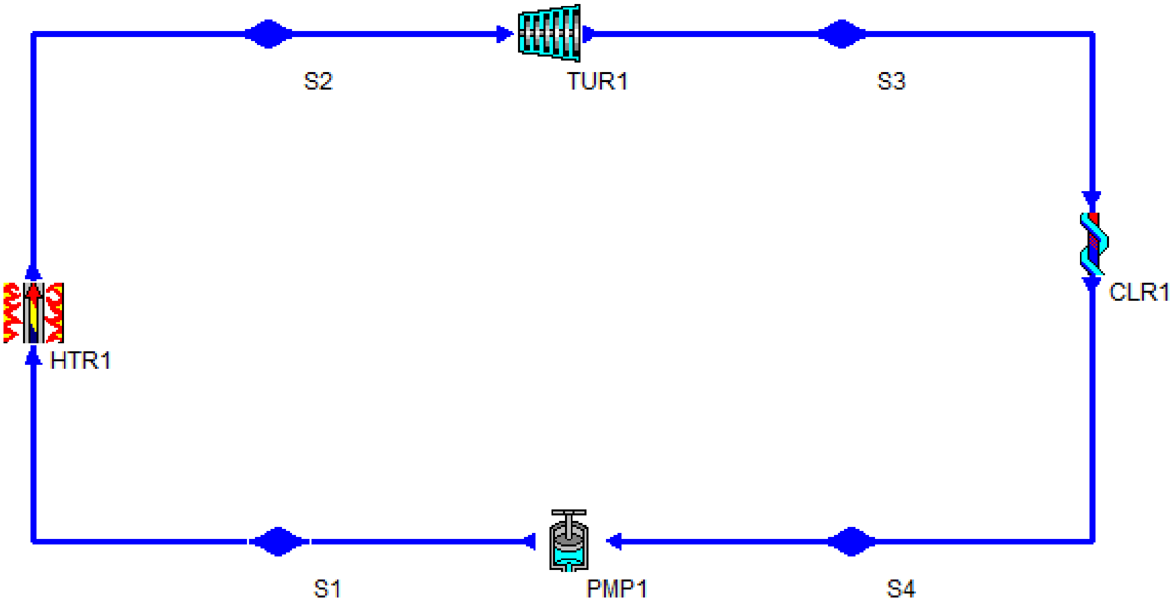
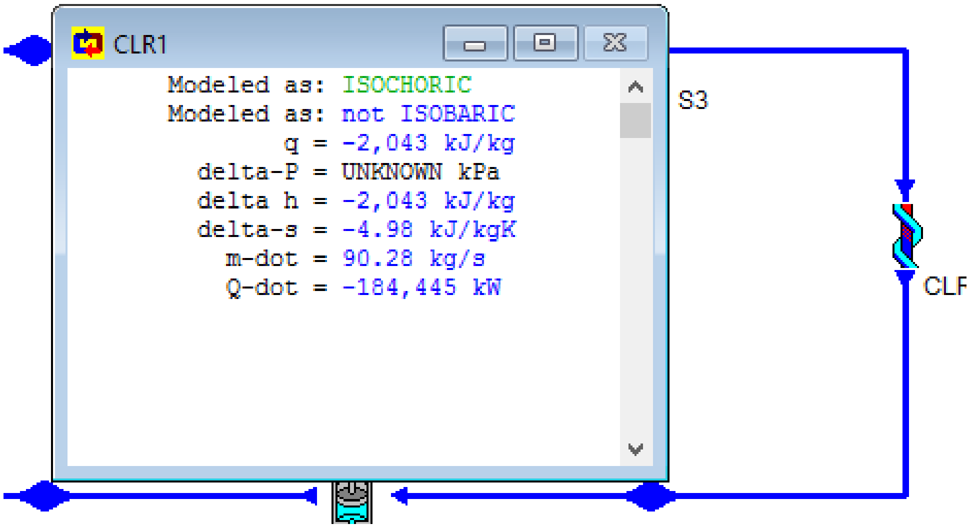


Figure (4.2) Rankine cycle

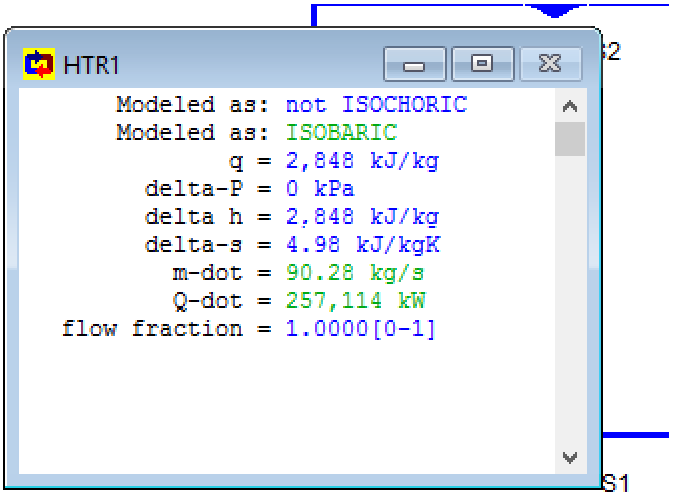
3- Enter the properties of the cycle: as shown in figures below:

i. Boiler pressure, temperature, or the energy released.
ii. Condenser pressure, temperature, or the energy rejected.
iii. Turbine output power.
iv. Pump input power.
v. Phase of water in each nodes.
vi. Boiler, turbine, condenser, and pump assumptions like is it isentropic, isobaric... etc.
vii. Mass flow rate of steam.



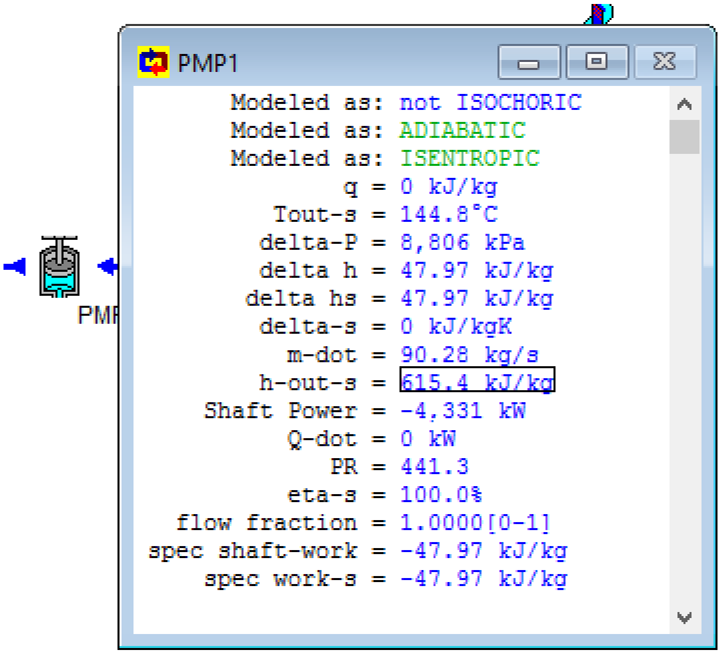
```
Modeled as: ISOCHORIC
Modeled as: not ISOBARIC
         q = -2,043 kJ/kg
   delta-P = UNKNOWN kPa
   delta h = -2,043 kJ/kg
   delta-s = -4.98 kJ/kgK
     m-dot = 90.28 kg/s
     Q-dot = -184,445 kW
```

Figure (4.3) Condenser properties



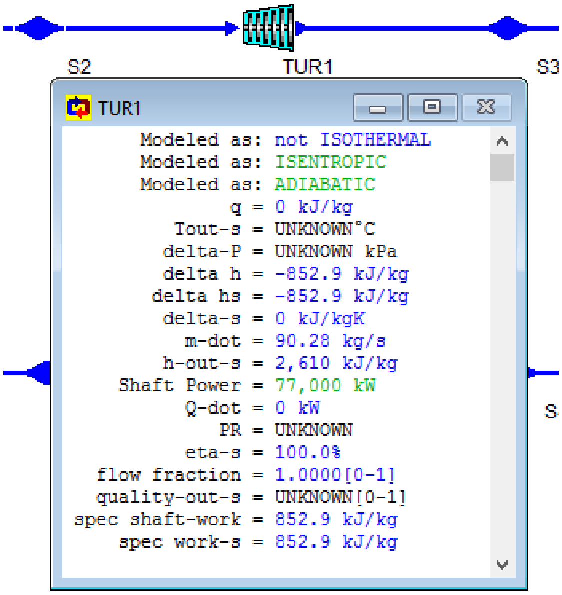
```
     Modeled as: not ISOCHORIC
     Modeled as: ISOBARIC
              q = 2,848 kJ/kg
        delta-P = 0 kPa
        delta h = 2,848 kJ/kg
        delta-s = 4.98 kJ/kgK
          m-dot = 90.28 kg/s
          Q-dot = 257,114 kW
  flow fraction = 1.0000[0-1]
```

Figure (4.4) Boiler properties



```
      Modeled as: not ISOCHORIC
      Modeled as: ADIABATIC
      Modeled as: ISENTROPIC
                q = 0 kJ/kg
           Tout-s = 144.8°C
          delta-P = 8,806 kPa
          delta h = 47.97 kJ/kg
         delta hs = 47.97 kJ/kg
          delta-s = 0 kJ/kgK
            m-dot = 90.28 kg/s
          h-out-s = 615.4 kJ/kg
      Shaft Power = -4,331 kW
            Q-dot = 0 kW
               PR = 441.3
            eta-s = 100.0%
    flow fraction = 1.0000[0-1]
 spec shaft-work = -47.97 kJ/kg
      spec work-s = -47.97 kJ/kg
```

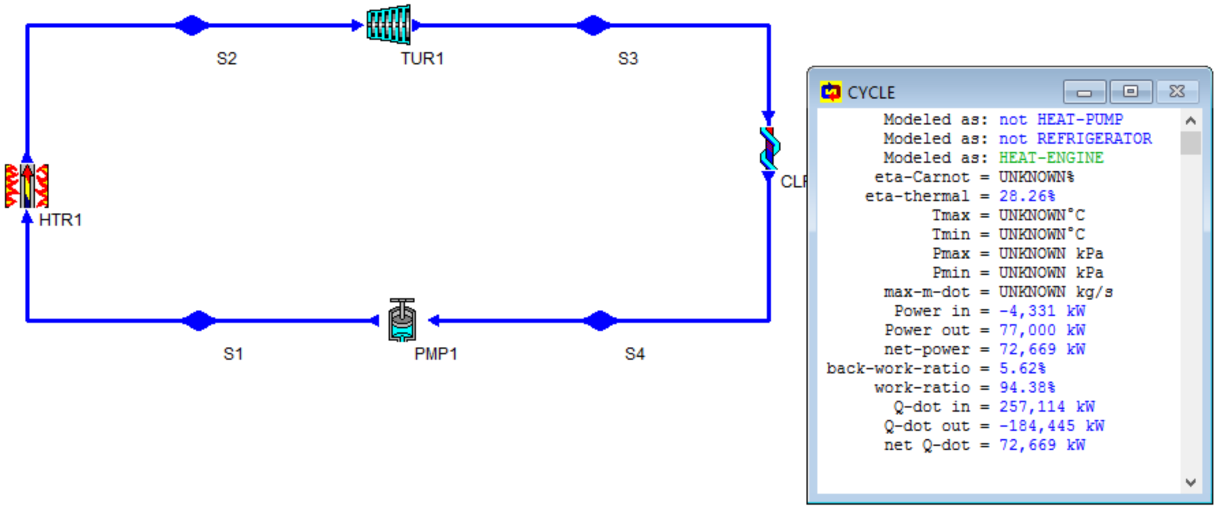
Figure (4.5) pump properties



```
TUR1
      Modeled as: not ISOTHERMAL
      Modeled as: ISENTROPIC
      Modeled as: ADIABATIC
               q = 0 kJ/kg
          Tout-s = UNKNOWN°C
         delta-P = UNKNOWN kPa
         delta h = -852.9 kJ/kg
        delta hs = -852.9 kJ/kg
         delta-s = 0 kJ/kgK
           m-dot = 90.28 kg/s
         h-out-s = 2,610 kJ/kg
     Shaft Power = 77,000 kW
           Q-dot = 0 kW
              PR = UNKNOWN
           eta-s = 100.0%
   flow fraction = 1.0000[0-1]
  quality-out-s = UNKNOWN[0-1]
spec shaft-work = 852.9 kJ/kg
    spec work-s = 852.9 kJ/kg
```

Figure (4.6) Turbine properties

4- Making the cycle analysis:



```
CYCLE
         Modeled as: not HEAT-PUMP
         Modeled as: not REFRIGERATOR
         Modeled as: HEAT-ENGINE
         eta-Carnot = UNKNOWN%
        eta-thermal = 28.26%
               Tmax = UNKNOWN°C
               Tmin = UNKNOWN°C
               Pmax = UNKNOWN kPa
               Pmin = UNKNOWN kPa
          max-m-dot = UNKNOWN kg/s
           Power in = -4,331 kW
          Power out = 77,000 kW
          net-power = 72,669 kW
    back-work-ratio = 5.62%
         work-ratio = 94.38%
           Q-dot in = 257,114 kW
          Q-dot out = -184,445 kW
          net Q-dot = 72,669 kW
```

Figure (4.7) Cycle analysis

4.3 Analysis and discussion:

-By comparing between the efficiencies of the two unit, it’s clear that Ph3 is more efficient than Ph2:

1-because it was operating with under half load, as was shown in fig (2.19), either Ph2 operated in a partial half load.

2-Ph3 is operating in a warm weather, the indicated temperatures was about 35℃.

Comparing with Ph2 which operated at a relatively cold weather about 27℃, also that it show in fig (2.19).

3-Also Ph2 has a high quantity of an air ingress, about a 38mbar, comparing with Ph3 about 16mbar, this can explaining that Ph2 is an old unit comparing with Ph3, which insulated in 2010.

4- Ph3 uses vacuum pump and it’s more efficient than SJAE which used in Ph2.

5- Also it’s clear that from the charts below:

Increasing of back pressure results on increasing of fuel consumptions, and increasing of steam load.

6- Also based on the above calculation, the cleanliness factor is 25.41, and it’s lower than the designed value of 0.818, indicating that the heat transferring side of tube is severely polluted.

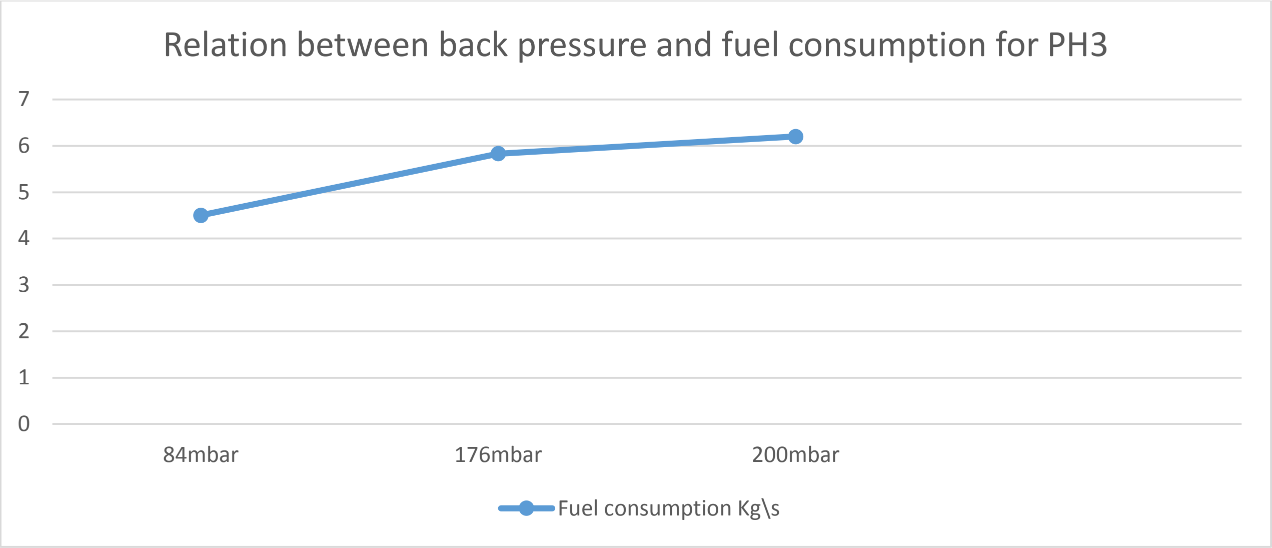


Figure (4.8) Relation between backpressure & fuel consumption

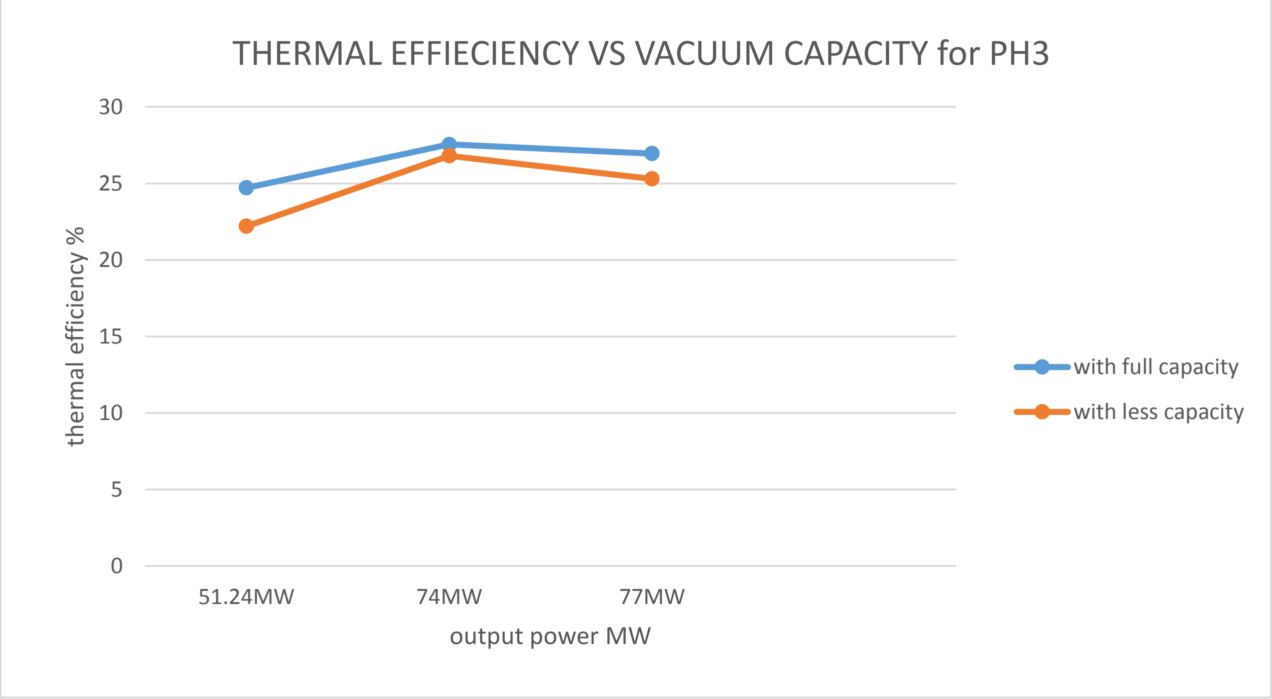


Figure (4.9) Thermal efficiency vs vacuum capacity for Ph3

4.3 Correct Sizing of Air Extraction Systems:

The information needed to accurately size a liquid ring vacuum pump includes:

- Suction pressure
- Suction temperature
- Mass flow rate and the molecular weight of fluid components
- Vapor pressure for each fluid component
- Seal fluid data, if other than water
- Temperature of seal fluid or cooling water
- Discharge pressure [18]

1-The Heat Exchange Institute of the USA (HEI 1995, p.30) specifies that the condenser venting equipment shall be designed for a suction pressure (3.39 kPa abs.)

2- The HEI (1995, p.30) also provides guidance on the venting system design suction temperature:

Suction temperature = steam saturation temperature at 3.39 kPa - 0.25(condenser saturation temperature- circulating water inlet temperature)

=26.1- 0.25(48.41-25) = 20.25℃.

3- Using the previously obtained design suction temperature of 20.25℃ and pressure of 3.39 kPa absolute, the water vapor load from Appendix E can be read off as:

W = 2.05 kg water vapor/kg of dry air.

4- To optimize the capacity of the air extraction system, the design capacity will be based on the HEI maximum recommended air in-leakage rate of 142 liters/min at the condenser design operating pressure of 9.5-kPa absolute. This capacity selection will also reduce the potential for LRVP cavitation developing, as the capacity will be closer to actual air in leakage rates.

This dry air discharge flow needs to be converted to a saturated mass airflow at the LRVP suction and a Dry Air Equivalent (DAE) found. The design air extraction rate at a condenser pressure of 3.39-kPa can be found by using equation:

$$Q_{new} = Q_{knowm} \times \frac{\sqrt{P_{atmosphere} - P_{new}}}{\sqrt{P_{atmosphere} - P_{known}}}$$

$$\therefore Q_{new} = 142 * \sqrt{\frac{101325-3390}{101325-7900}} = 145.4 \text{ liters/min.}$$

-to be converted to an air mass flow rate:

$$\dot{m} = Q \times \rho \times \frac{60}{1000}$$

$\therefore \dot{m}$=145.4 *1.204*60/1000 = 10.5 kg/h

-Because the mass flow rate is dry air, the value of 2.05 kg of water vapor/kg of dry air may be used, from the HEI’s Appendix E. At the air extraction suction temperature of 21.7 °C, the specific volume of steam is vg = 57.02 m3/kg, and it takes 2.05 kg of steam to saturate each kg of dry air.

-The volume of steam required to saturate the 10.5 kg/h of dry air at 20.25 °C is then:

$$\therefore \dot{V} = 10.5 \times 57.02 \times 2.05 = 1227.4\ m^3/h$$

The density of the air at the air extraction suction pressure of 3.39 kPa and 20.25 °C can be calculated using equation:

$$\therefore \rho = \frac{3390}{287 \times 293.25} = 0.0403\ \text{Kg}/m^3$$

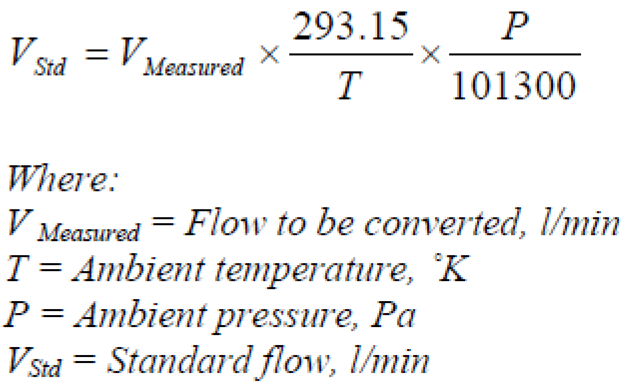
The specific volume of the air is then:

$$\text{Vg} = \frac{1}{\rho} = \frac{1}{0.0403} = 25\ m^3/\text{Kg}$$

The volume of air at the suction is then:

$$\therefore V\,Air = 25 \times 10.5 = 262.5\ m^3/h$$

After adding the steam and air volumes at the suction these can then be converted to a standard dry air equivalent at 20 °C and 101.3 kPa by using equation:



$$V_{Std} = V_{Measured} \times \frac{293.15}{T} \times \frac{P}{101300}$$

Where:

$V_{Measured}$ = *Flow to be converted, l/min*

T = *Ambient temperature, °K*

P = *Ambient pressure, Pa*

V_{Std} = *Standard flow, l/min*

$\therefore$DAE = (1227.4+262.5) $\times\frac{293.15}{293.40}\times\frac{3390}{101300}$= $49.82 m^3/h$.

$\therefore$DAE= 830.3 liters/min.

To achieve a HEI recommended target condensate dissolved oxygen level of 42 ppb an actual load divided by the design capacity ratio of 0.50 must be used:

$\therefore Q_{design} = \frac{830.3}{0.5}$= 1660.57 liters/min.

Chapter five

Conclusion & Recommendation

5.1 Conclusion:

According to the study:

1. The Power output of steam generation effected by the air ingress and tube fouling.
2. Ph3 thermal efficiency is 24.71%, Ph2 thermal efficiency is 28.7%, but Ph3 is more efficient as mentioned in chapter four.
3. Any present of increasing of backpressure causes an increase in fuel consumption, and steam load.
4. The correct size of the vacuum pump of Ph3 must be 1660.57 liter\min.

5.2 Recommendations:

Recommendations to KNPS managers:

1. Replacing the vacuum system of Ph2 by vacuum pump.
2. Replacing the vacuum pump of Ph3 by a vacuum pump with capacity of 1660.57 liter\min.
3. Take care of Condenser tube cleaning.

Recommendations to mechanical engineering department:

1. Making a lot more studying about condenser backpressure, with another parameters.

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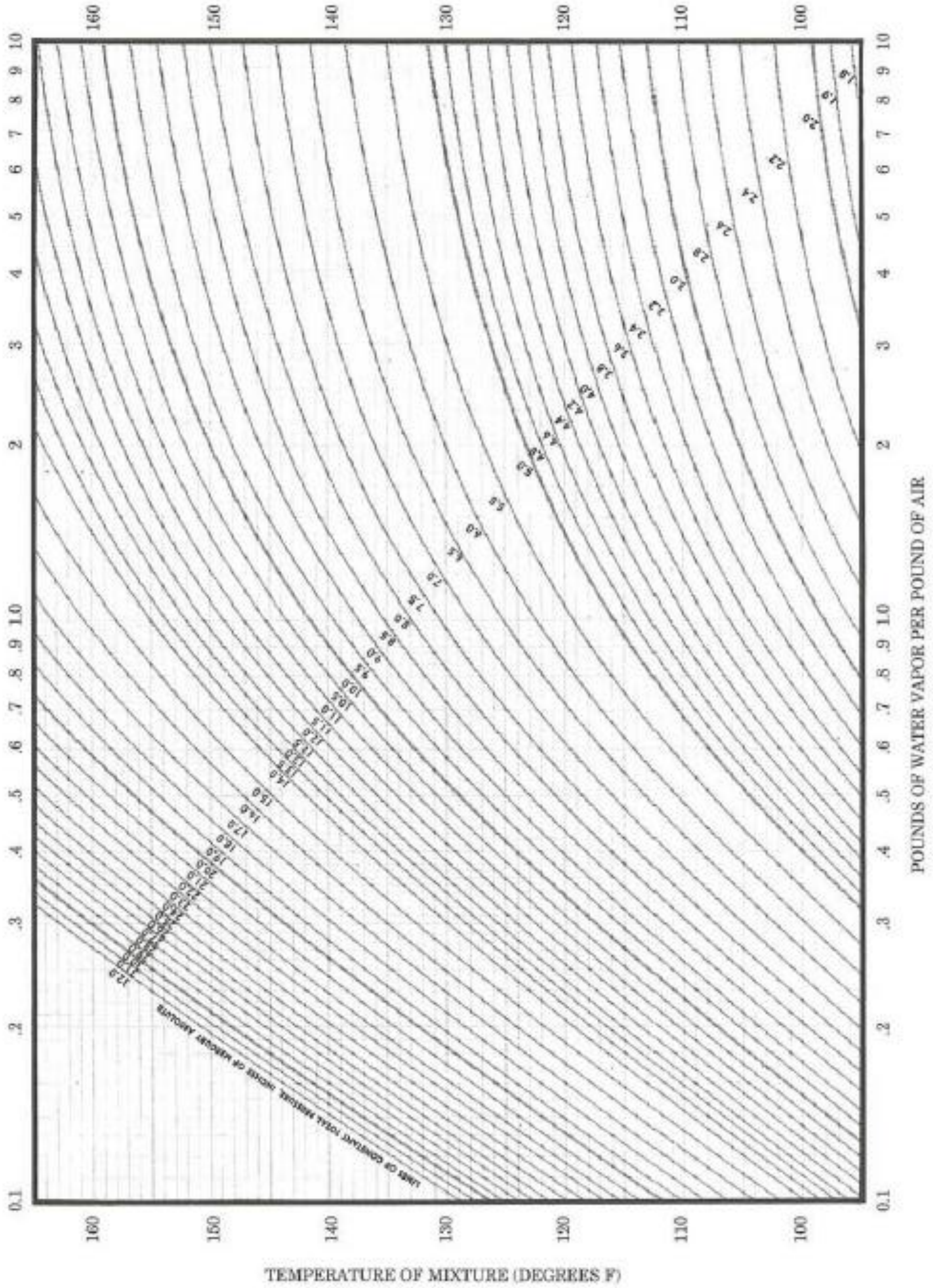
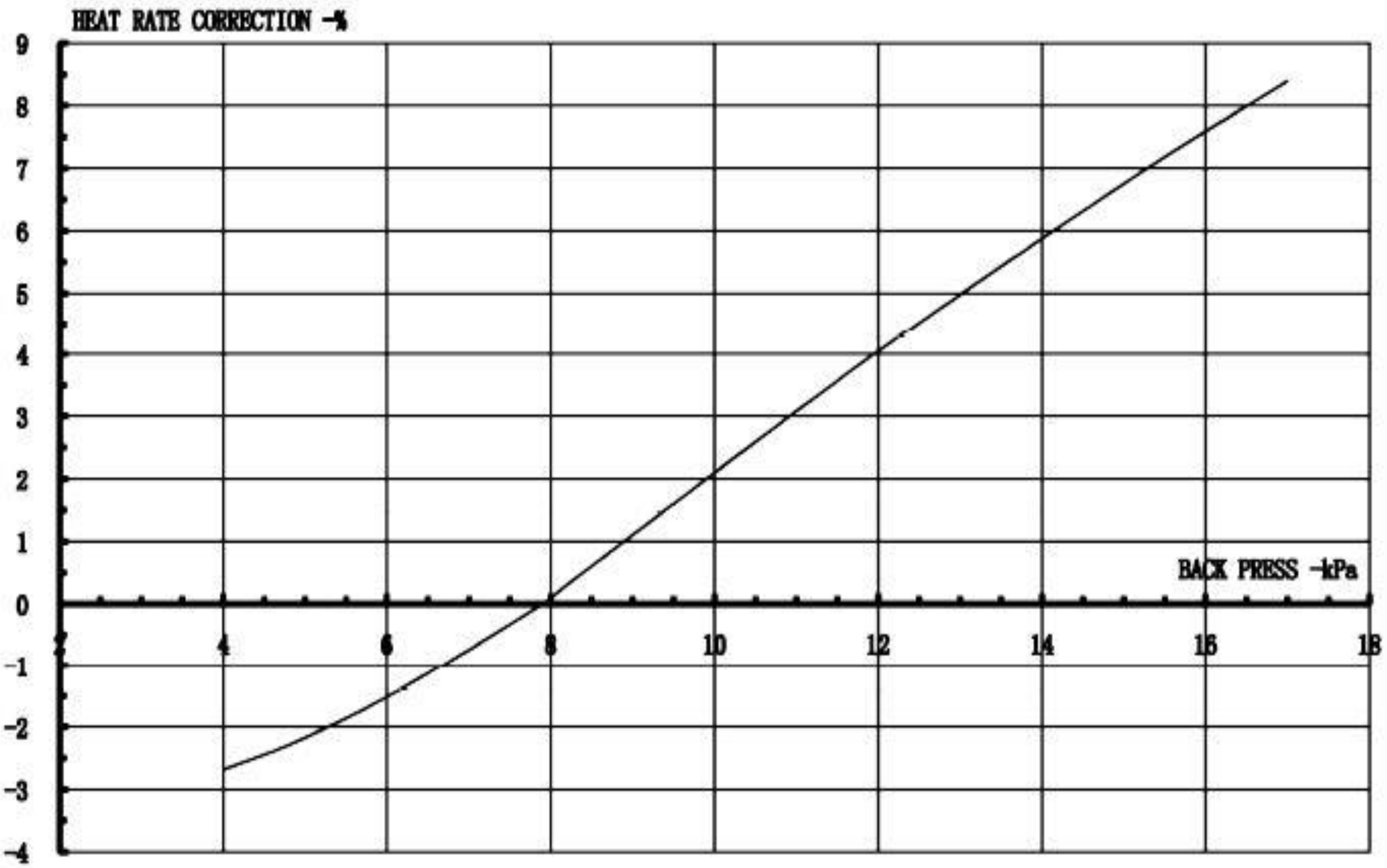
APPENDIX E

AIR AND WATER VAPOR MIXTURE DATA (DALTON'S LAW)




HEAT RATE CORRECTION -%
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
2
4
6
8
10
12
14
16
18
BACK PRESS -kPa