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Introduction to Thermo Vacuum Pump and its impact on maximizing the efficiency of the thermal power plants

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Abstract: *This work deals with Power Plants Technology. We here take an interest on how to maximize the work delivered by the steam turbines using the so-called Thermo Vacuum Pump (TVP). This work represents a design innovation paper proposed in a theoretical emphasis.*
There is a knowledge gap in utilizing the Condensation in maximizing the overall efficiency of the Thermal Power Plants. The paper basically aims to propose the TVP as a new method to close this gap where the Air Cold Condenser type is used.
Thermo vacuum pump (TVP) is a thermodynamic machine increases and controls the vacuum at the steam turbine outlet by circulating specific amount of condensate, or steam in some cases, and injecting it in engineering manner into the steam stream at the condenser inlet again.
This paper justifies the research results using theoretical equations because the paper is aimed at providing a basic knowledge about the TVP. However, the paper confirms the validity of a new design opportunity, in principle, which needs further work out in the future.
Anyhow, installing TVP will basically (1) enable to increase the loading capacity of the steam turbine at winter and (2) enable to reduce the load reduction at summer.

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I. Introduction

A power Plant, also referred to as a generating station, power station or generating plant, is an industrial facility for the electricity generation. Each power station contains one or more electric generator, which is a rotating machine that converts mechanical power into electrical power by creating relative motion between a magnetic field and an electrical conductor. The energy source harnessed to turn the generator varies widely. It can be a Diesel Engine, Steam Turbine, Gas Turbine or any other mechanism that delivers a power on a shaft. Most power stations in the world burn Fossil fuel such as coal, Petroleum, and Natural Gas to generate electricity, and some use Nuclear Power, but one of the most conventional types is the steam cycle power plant, which is referred also to a Thermal Power Plant [1]. In a conventional thermal or steam turbine plants, fuel is burned in the boiler furnace in order to heat water in the boiler and convert it into hot steam. The superheated, high-pressure steam is then piped to rotate the steam turbine at fixed revolution speed, thus spinning the generator, which is connected directly with the turbine shaft. In this way, electricity is produced and adjusted for further transmission. After driving the turbine, the exhaust steam from the low-pressure turbine is passed into the condenser where hot steam is condensed into water to be reused in the boiler [2]. Thermal power plants are outstanding because of their high efficiency, capacity, and long service life. Besides, they can burn various kinds of fuel, such as natural gas, oil and lignite. However, due to their much time-consuming for startup, thermal facilities they usually run continuously all day long to provide base load for the electrical grid or the industrial facility.

All thermal power plants produce waste heat energy as a byproduct of the useful electrical energy produced. The amount of waste heat energy equals or, in most cases, exceeds the amount of energy converted into useful electricity. Gas-fired power plants can achieve in some cases as much as 65% conversion efficiency, while coal and oil plants achieve around 30–49% [3]. The waste heat produces a temperature rise in the atmosphere, which is small compared to that produced by greenhouse gas emissions from the same power plant. In Thermal Power Plants, the exhaust steam from the turbine outlet is condensed conventionally by two cooling mediums; either by the water in the so- called Water Cold Condenser (WCC) or by the ambient air in what is called Air Cold Condensers (ACC), which in turn is divided into directly - air cold condensers and indirectly - air cold condensers. Anyhow, in such large- scale process, the facility used to control the steam condensation and the cooling medium flow rates is called "Cooling Tower". The "Indirect" cooling method means that the steam is condensed by a cooling medium, in a closed loop, that is: cold by another medium. The indirect air cold condensers can divided into natural draft and induced draft type. Natural draft wet cooling tower at many nuclear power plants and large fossil fuel-fired power plants use large hyperboloid chimney-like structures that release the waste heat to the ambient atmosphere by the evaporation of water [3]. However, the mechanical induced-draft or forced-draft wet cooling towers are commonly used in many large thermal power plants, nuclear power plants, fossil-fired power plants, petroleum refineries, petrochemical plants, geothermal, biomass and waste-to-energy plants. They use fans to provide air movement upward through down coming water, and are not hyperboloid chimney-like structures. The induced or forced-draft cooling towers are typically rectangular, box-like structures filled with a material that enhances the mixing of the up flowing air and the down flowing water [4]. In areas with restricted water use, a dry cooling tower or directly air-cooled condensers may be necessary, since the cost or environmental consequences of obtaining make-up water for evaporative cooling would be prohibitive. These coolers have lower efficiency and higher energy consumption to drive fans, compared to a typical wet, evaporative cooling tower. They dry cooling method is one of the most used methods because of the current water crisis in the world, and the increasing need to minimize the consumption rates in the natural recourses on the earth.

In this work, Thermo vacuum pump principle will be studied in Directly Air Cooled Condensers. The research problem will be explained in the following section and the case will be defined as an engineering challenge. The opportunity, which is the Thermal Vacuum Pump, will be proposed theoretically. TVP definition, working principle will be explained as well as how it can be utilized to increase and control the steam turbine load. Afterwards, the modeling equations of Thermo Vacuum pump and a simple model of it will be introduced. The paper will go through some design and control variables and give an example on how the TVP will be installed on a power plant.

II. The Challenge

In Rankin Cycle, the work produced from the fluid expansion depends mainly on the difference between the enthalpy across the turbine as well as the mass flow rate of the steam. So at certain mass flow rate, more shaft power can be generated when the enthalpy difference between the turbine inlet and outlet is greater. Therefore, the thermodynamic properties at turbine outlet represent a good opportunity to enhance the performance of the turbine. The outlet pressure of the steam turbines is set under the atmospheric pressure in order to generate as much shaft power as possible. Then, at the same turbine inlet pressure, the lower the outlet pressure, the higher the generated shaft work. The difference in the produced shaft power can be sensed practically if two thermal power stations, one with ACC and the other with WCC are compared. The sent out efficiency in the ACC plant type reaches to 33% like in the second unit in Al-Husain Thermal power plant in country of Jordan. However, the sent out efficiency comes to 34.07% in the WCC type like in Al-aqaba power plant (unit 3), which is located around 300 Km from Al-Husain Thermal power plant [6, 7].

When the site conditions of the steam turbine vary from time to time throughout the year, the optimization of the design parameters becomes more complex because the same turbine must perform well in different boundary conditions. These design parameters are like the turbine outlet dimensions, the turbine outlet pressure, diffuser sizing, and the blades number, configuration, and sizing. So for example, a turbine installed in a dry area in the Middle East like in Mecca city [5] in Saudi Arabia will not be basically have the same design parameters as a turbine installed in Irkutsk city in Russia because the range of the ambient temperature degrees varies in Irkutsk (-50 C – +37 C) throughout the year whereas it comes between (+10 C – +50 C) in Mecca. In addition, Mecca city has no access to use the water in the condenser cooling unlike Irkutsk.

However, one of the most commonly used ways to optimize the design parameters in the Air Cold Condensers (ACC) is to control the radiators fans speed. In the ACC, the air is circulated forcedly by means of fans, which have two or more speed settings; at least high and low speed. The speed of the fans determines the mass flow rate of the cooling air and so the condensation rate. In the energy balance equation of the condenser, there are four factors to control the heat exchange, which are the steam flow & temperatures and the air flow rate & temperatures. The steam flow at certain load is constant and the steam inlet and water outlet temperatures at the inlet and outlet of the condenser are constant because of the phase change. So, the only factor that determines the fan speed (air mass flow rate) is the air temperature, i.e. the ambient temperature. Therefore, at summer when the ambient temperature is high, the fans speed needs to be set at high speed so as to maintain the desired condensation rate. The condensation rate is important because it is determines the design outlet pressure of the turbine. From the other hand, at winter, the fans speed is set at low speeds because the ambient temperature is low respectively. In addition, the low air temperature enables to increase the condensation rates. In this case, more negative pressure can be maintained at the turbine outlet enabling more shaft power to be produced.

Although the fans speed control method is an effective way to close the gap between the design parameters at winter and summer, there is still some deficiency to better close the aforementioned gap. One important design restriction is that the fans speed cannot be set at high speed at winter because more negative pressure can be established at the turbine outlet. In this case, the drag force at the turbine outlet will be greater which will cause turbine over speed. The turbine over speed will take place because the turbine inlet admission valves are designed to meet the steam demand at summer so they won't admit more at winter so as the admitted steam quantity will be accelerated beyond the design limit due to the greater drag force at the turbine outlet. The design steam flow rate at the inlet cannot be increased because the turbine outlet drag force at summer won't be sufficient to smoothly expand the admitted steam through the turbine. In other words, neither the fan speed can be increased at winter in order to extract more shaft power nor more steam can be admitted at the turbine inlet at summer. The first restriction is at the turbine inlet in order to prevent the steam over acceleration and the second restriction is at the turbine outlet in order to prevent the steam deceleration. This clearly addresses a knowledge gap in the thermal power plants design.

Another problem is introduced due to the conflict between the winter and summer boundary conditions. A turbine load reduction takes place when the ambient temperature goes beyond the average values in the area because the maximum fans speed is not capable of maintaining the design condensation rates and, hence, the design negative pressure at summer. The maximum design fans speed is also determined in shade of the winter conditions so as it there won't be much extra fans capacity at winter.

The interest in this paper is taken on how to close the aforementioned knowledge gap. The methodology is to study how some of the design deficiency can be mitigated by circulating some steam from the condenser into the steam turbine intermediate- low pressure stages instead of admitting more steam at the inlet, and then if more shaft power can be generated at winter when setting the fans speed at high speeds.
In the literature survey carried out by the researcher, there was no paper discussed such an opportunity to maximize the overall efficiency in the thermal power plants.

III. The Opportunity (Thermal Vacuum Pump)

The Condensation and Negative pressure

In a fluid phase change[1], the density of the fluid decreases considerably creating free spaces in the flow stream, which is called Vacuum. The vacuum drags the adjacent fluid particles from the upstream to fill the free vacancies due to continuity of the fluid flow. In other words, the vacuum is the driving force that works toward dragging, not pushing, the fluid toward downstream due to the Continuity of the fluid. The fluid particles tend to take the easiest path and will not flow back as the fluid particles are more congested there. Figure1 shows that the volume occupied by the fluid in the gas phase is more than the volume occupied by the same mass of the liquid phase because of the higher molecular interaction in the liquid phase. This means that a free space equals the difference between the two volumes shown in the figure 1, will be delivered instantly when the condensation is taking place.

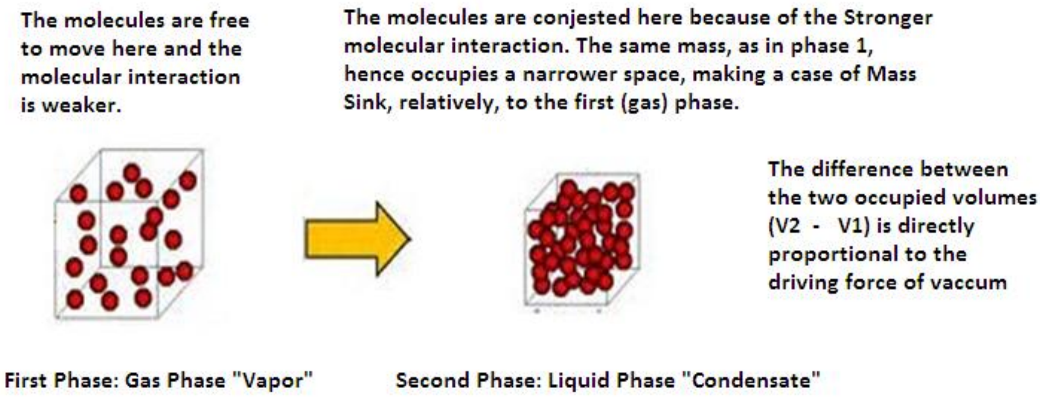

Figure 1 the volume occupied by the fluid in the gas phase is more than the volume occupied by the same mass of the liquid phase because of the higher molecular interaction in the liquid phase. In such a way the condensation creates vacuum.

The negative pressure delivered in a phase change process depends on the mass flow rate of the gas to be condensed.

$$-\Delta P \propto \dot{m} \qquad (1)$$

[1] This section is introduced at the college level so as the research paper is absorbable by more audiences and covers different sectors of readers.

The pressure of the fluid in stream is maintained through the interaction between the different parts of the stream. However, the fluid behavior as a whole is quite self- adaptive and reactive as the small change in some part of it is contained by the fluid as a collective. Therefore, in order to study how the force effects on the fluid if applied somewhere in the stream, the fluid is divided imaginary into three sections, force center, upstream and downstream. Figure 2 and Figure 3 depicts how the fluid parts adapt making the variance of the local differential pressures (forces) into a one united value throughout the fluid stream.

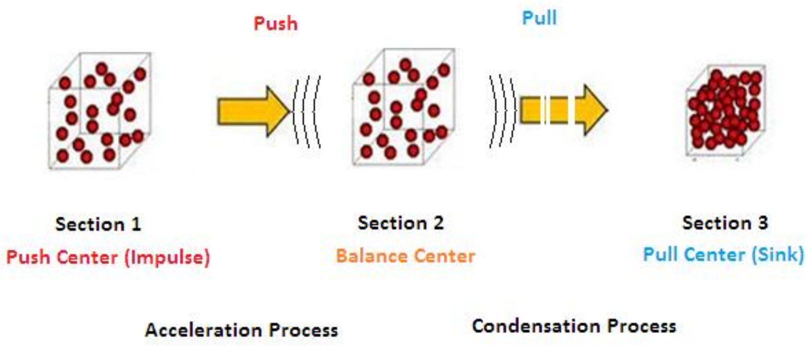

Figure 2 how the fluid parts adapt during the condensation process so it delivers negative pressure

In the sections taken in the analysis, there are three sections, sections one (Push Center), Section 2 (Balance Center) and Section 3 (Drag Center) or (Pull center). This picture can be generalized throughout the fluid, so every section in the fluid stream is a balance center with respect to the upstream and downstream sections. Similarly, every section in a fluid is a Push or Pull center with respect to the downstream or upstream sections when a force is applied on the fluid. The behavior of the balance center determines how the fluid will resultantly adapt to the external and internal forces in the fluid stream. Hence, the negative pressure and the positive pressure can be both defined using the balance center. So the negative pressure can be defined, as in figure 3, as property of the fluid that results when the push force toward the Balance Center equals to zero with respect to drag force on the balance center. Nonetheless, the positive pressure on a fluid is the property that results when the Pull Force on the balance center equals to Zero with respect to the push force on the balance center.

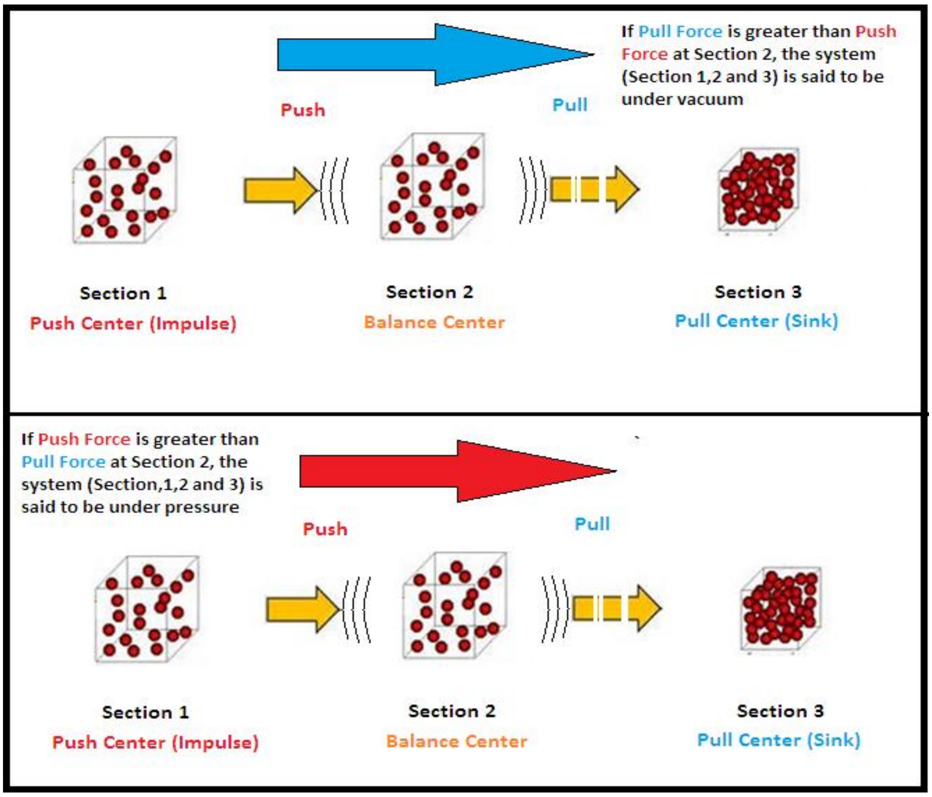

Figure 3 How the Negative and Positive Pressures are defined using a three sections model in the fluid stream

However, in order to control or create any change in the fluid stream it is important to focus on the Balance Center (Section 2). In the Thermo vacuum pump, the Balance center is where the condensation process takes place as seen in Figure 2. In order to control the process during the condensation, the relationship between the vacuum and the mass flow rates must be studied. The mass flow rate can be expressed in terms of linear velocity (u) and cross sectional area (A), then,

$$-\Delta P \propto \Delta(u.A) \quad (2)$$

As the equation shows, the difference between the velocities at the inlet and outlet and the difference between the cross sectional areas at the inlet and outlet are the control elements in the process as they are directly proportional to the created delivered pressure.
Then again in case of considering vacuum control at section2;

$$-\Delta P \propto (u_{out}.A_{out} - u_{in}.A_{in}) \quad (3)$$

This equation implies that in order to increase the negative pressure delivered, the outlet linear velocity and cross sectional areas must be greater than the inlet ones.
If the system is receiving extra mass across its boundaries, then the latter equation must be changed into the following;

$$-\Delta P \propto (u_{out}.A_{out} - u_{in}.A_{in}) \mp \dot{m}_{ext} \quad (4)$$

Where $\dot{m}_{ext}$is the mass flow rate being added or removed from the system. The sign $\mp$ here does not refer to mass adding or removal, but it refers to the effect of the mass on the fluid dynamics, i.e. whether it causes flow congestion (minus sign) or creates extra spaces (positive sign).

Thermo Vacuum Pump Definition

Thermal Vacuum Pump is a thermodynamic machine that creates and controls the negative pressure in a fluid stream by means of the phase change (condensation). In shade of the background introduced in the previous section about how to control the mass flow rate during the condensation, a simple model of Thermo vacuum pump models can be introduced as in figure 4, where there is a divergent - constant - convergent tube with water injection as shown. The heat removal should take place along the tube, but the heat transfer rate should be more near the constant section.

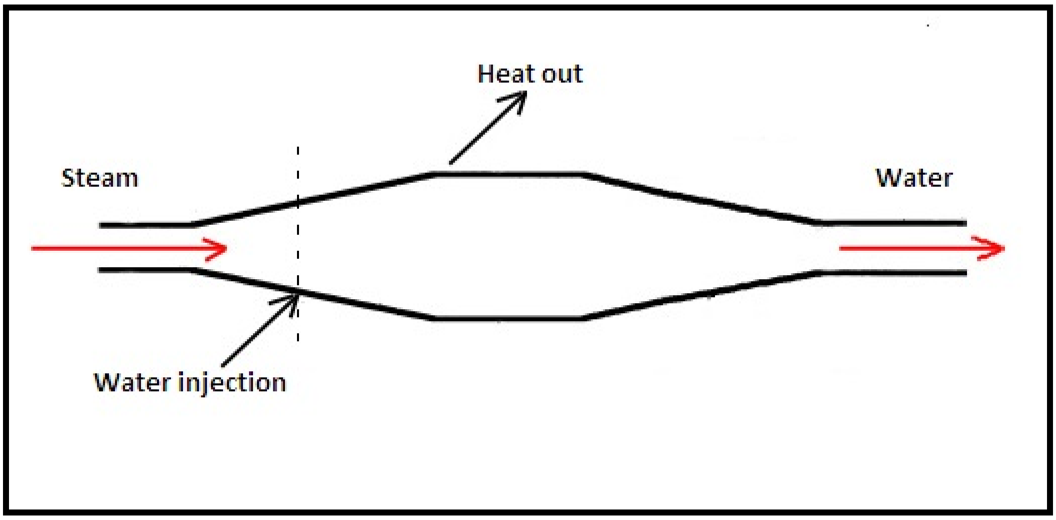

Figure 4 A simple model of the thermo vacuum pump

How TVP works in a Thermal power plant

At winter there is an opportunity to admit more steam to the turbine because of the good cooling capacity at the ACC. As the steam mass flow increases, the negative pressure at the turbine outlet increases due the condensation of extra steam in the condenser. TVP works to circulate some condensate from the condenser outlet and injecting it back in the steam stream in form of steam. Therefore, more negative pressure can be maintained at the turbine outlet without admitting more steam at the inlet. Moreover, a steam flow can be secured at the turbine, so avoiding the problem of turbine over speed. The simple model of the TVP shown in figure 4 will contribute to improve the delivered negative pressure.
TVP can come in one of the following designs;

- The condensate is recirculated from the condenser outlet and piped through a tube heat exchanger gains the heat from the turbine heat loss, or from the turbine exhaust and heat exchanger before entering the condenser in form of steam. This represents a heat recovery design.
- The condensate is pumped after the condensate extraction pump to a high-pressure pump and pumped back into the condenser through special nozzles that assures full atomization.
- The recirculated condensate is heated using the ejector and the gland seal condenser.
- The condensate is recirculated and the TVP is combined with another supporting system like the fogging system in the combined cycle plants at the dry places. Such system can be integrated with the thermo vacuum pump using the same injection pump. This will reduce the capital cost of the two systems comparing with the extra capacity they provide at both of the hot (fogging system) and cold weathers (TVP).
- After pressurizing the circulated condensate using high pressure pumps, it then cooled using heat exchanger (cooler) and, or, through the adiabatic expansion in the nozzles. The cooled water will assist the condensation process in the condenser in addition to its function in the TVP.
- The circulated condensate is piped to an economizer. The economizer has a dual function, it either reheats the saturated steam in order to add it back into the low pressure turbine or reheat the saturated water in order to add it again in the condenser in form of steam or both of them. This solution is more affordable in the thermal plants with reheat cycle. In the two ways the TVP will work to improve the vacuum because more steam is piped to the condenser.

An example of steam cycle plant with TVP
In this section, the TVP will be installed in an illustrative example to a steam cycle plant with two Feed Water Heaters (FWH's). The possible scenarios after installing the TVP in the cycle will be clarified.
Cycle A (without TVP)

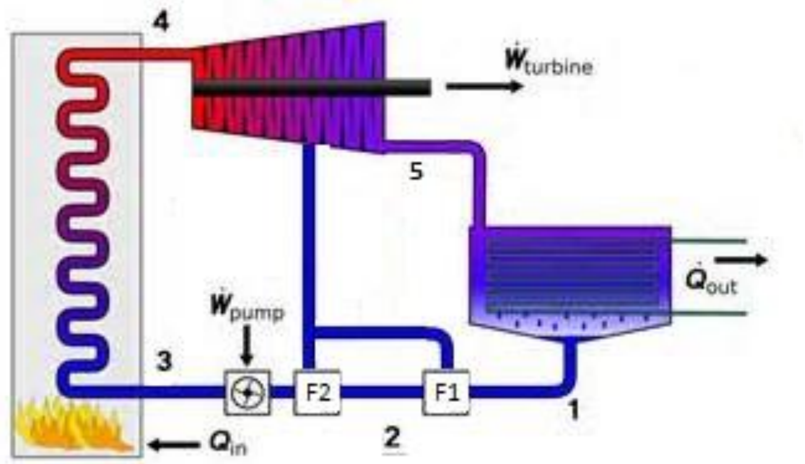

Figure 5 simple representation of a steam cycle plant with TWO FWH's before utilizing the thermo vacuum pump. F1 is the FWH 1 and F2 represents FWH2.

Cycle with TVP:

The cycle with TVP is simply represented in figure 8. As seen, some condensate is picked from the outlet of the condenser, recirculated and pressurized using a high pressure pump and then it will be injected through nozzles in the steam stream and mixed thoroughly in order to generate more vacuum. It is of importance to assure that the water injected is colder than the steam so it can vaporize easily. Moreover, the injection will help in the vaporization. This double effect works toward increasing the vacuum through increasing the mass to be condensed and accelerating the condensation of some sections in the steam stream so that avoiding the congestion and the over friction at the steam stream.

To cool the recirculated condensate, another heat exchanger (radiator) might be required. As shown in figure 6, the energy rejected from the air cold condenser can be utilized instead of installing a new heat exchanger.

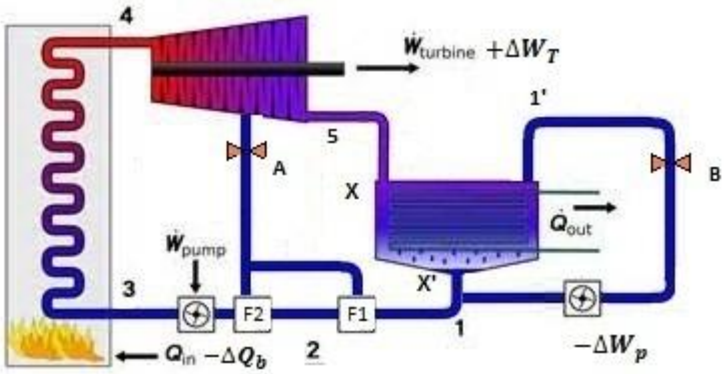

Figure 6 simple representation of a steam cycle with thermo vacuum pump. F1 is the FWH 1 while F2 represents the FWH2.

The mass flow rate after point 1 (Condenser outlet) toward the main cycle will be less than it used to be after the recirculation starts. This will enable to admit more effective steam into the steam turbine in order to deliver more work through diverting some steam from the feed water heater to the steam turbine itself. The steam demand at the feed water heaters will decrease because some of the condensate already has been taken to the thermo vacuum pump, so the steam mass flow rate required to preheat the condensate will be lesser. This process can be controlled using the valves A and B. By throttling valve A, the effective steam that works toward increasing the work will increase, while the valve B controls the quantity of the re-circulated condensate, which is a function of the steam required in the feed water heater. A good instrumentation system and logical communication must be secured between these two valves.

In the boiler, there are two scenarios that can take place with the presence of TVP. The first scenario is to keep the highest temperature (after the boiler) constant by reducing the fuel to be burnt at the boiler. This scenario contributes toward decreasing the energy input. The second scenario is to keep burning the same fuel amount in the boiler, which means that the temperature at the boiler outlet will be maximized. These two scenarios will be applied on the Steam Turbine, where the effect of the first scenario appears on the turbine in a reduced mass flow rate with the same inlet temperature. The feed water heater steam that has not been involved in the economizing (preheating) process will be used here to compensate the steam mass flow rate by throttling the valve A. The effect in the second scenario appears in form of higher inlet steam temperature, whilst the outlet temperature will be less than it used to be without thermo vacuum pump.

As for the Condenser, the inlet and the outlet temperatures in each scenario will be the same as a phase change takes place so the temperature degree is constant. The difference between the two scenarios is in the mass flow rates, and so in the energy consumed by the condenser.

Modeling equations:

As an engineering innovation design, the TVP must be modeled and justified by experimental relationships that must be gained through a series of the experiments so as to validate the results of the study. Nonetheless, this paper justifies the research results through theoretical equations because the paper is aimed at providing a basic knowledge about the TVP. Therefore, the paper confirms the validity of a new design opportunity yet in principle, which will need further work out in the future. Based on aforementioned clarifications, this section explains the theoretical basis of the TVP principle by applying well-known thermodynamic and gas dynamics equations.

The negative pressure can be delivered and maintained by the condensation process depends on the change in the volume occupied by the gas and then the liquid phase. The volume change results from the phase change can be calculated using the following equation:

$$\Delta V = m\left(\frac{1}{\rho_g} - \frac{1}{\rho_l}\right) \tag{5}$$

This can be written in the following form as well,

$$\Delta V = m(v_g - v_l) \tag{6}$$

The volume rate of change ($\Delta\dot{V}$) can be calculated if the mass flow rate of the steam ($\Delta\dot{m}$) is known;

$$\Delta\dot{V} = \dot{m}(v_g - v_l) \tag{7}$$

The negative pressure delivered from the phase change process can be maintained if the mass flow rate of the condensing steam is controlled. The turbine accelerates the steam to a velocity so that the pressure at the outlet reaches the required negative pressure at turbine outlet. This value should be maintained by controlling the condensation rate $\Delta\dot{V}$. Therefore, if it is possible to increase ($\Delta\dot{V}$), then there is an opportunity to improve and maintain the vacuum at the turbine outlet so extra shaft power can be generated.

To calculate the vacuum results from the volume change, a control volume where the condensation takes place needs to be studied. However, for a certain mass of vapor, the condensation takes place gradually so there is no single zone to be studied so that to cover the condensation process as all with the analysis. Anyhow, the condensation zones can be divided generally into three major zones, saturated vapor zone (100% mass of vapor), mixer zone and at last the saturated water zone (100% mass of water). In other words, the condensation takes place gradually because the molecular interaction increases gradually. In such a process, the control volume can be taken either at a large scale or a very small scale. If it is studied at a large scale, then the condenser as a whole will be taken as a control volume where the condenser inlet represents the saturated vapor zone and the condenser outlet represents the saturated water zone whereas the mixer zone is represented by the condenser itself. So if the large scale to be taken in the analysis, the variables at the condenser inlet and outlet are subject of the analysis where all the changes in the condenser are neglected. However, TVP uses steam or water injection in several locations at the condenser. So in order to study the best design of the TVP it is important to study the process in a small scale then to generalize the picture and monitor what happens in the condenser as a whole control volume. In order to study the very small scale of the condensation, the assumption to be made is to study a very small differential part of the vapor mass. This part would be the closest the saturated vapor phase when the mass water mass fraction goes to zero. It is the first differential mass yet the smallest to be condensed.

Euler equation is valid in this case for the vapor and water during the phase change process, because it is applicable on both the compressible and incompressible flows.

$$\frac{dP}{\rho} = udu \tag{8}$$

To define the pressure P, the density should be expressed in terms of pressure. The equation of state is applied to substitute the pressure and the density;

$$P = R\rho T \tag{9}$$

R is constant and the condensation process is isothermal so R times T is constant. Then;

$$\rho = \frac{P}{RT} \tag{10}$$

By substituting this value into Euler equation;

$$RT\frac{dP}{P} = udu \tag{11}$$

By the infinite integration between ($P_1,\ u_1\ and\ P_2,\ u_2$);

$$\int_{P1}^{P2} RT\frac{dP}{P} = \int_{u1}^{u2} udu \tag{12}$$

It gives;

$$RT.\ln\left(\frac{P_2}{P_1}\right) = u_2^2 - u_1^2 \tag{13}$$

But the latter equation equals;

$$P_2 - P_1 = e^{(RT)^{-1}.(u_2^2 - u_1^2)} \tag{14}$$

And since $P_2 < P_1$, then;

$$\Delta P = -\, e^{((RT)^{-1}.(u_2^2 - u_1^2))} \tag{15}$$

This equation gives the pressure difference results in the thermo vacuum pump in terms of velocity. The velocity can be defined in terms of flow rate

$$u = \frac{\dot{V}}{A} = \frac{\dot{m}}{A.\rho} = v\frac{\dot{m}}{A} \tag{16}$$

If the flow is said to be steady and the cross sectional area is constant then;

$$u_2^2 - u_1^2 = (u_2 - u_1)(u_2 + u_1) = \frac{\dot{m}}{A}(v_{gf})(v_f + v_g) = \frac{\dot{m}}{A}v_{gf}(2v_f + v_{gf}) \tag{17}$$

So;

$$u_2^2 - u_1^2 = \frac{\dot{m}}{A}(v_{gf}^2 + 2v_f v_{gf}) \tag{18}$$

Then;

$$\Delta P = -\, e^{(\frac{\dot{m}}{ART}(v_{gf}^2 + 2v_f v_{gf}))} \tag{19}$$

The minus sign in this equation shows that the pressure here is negative pressure (vacuum).
This equation shows that the negative pressure delivered from the condensation depends on the vapor mass flow rate, the specific volume change, the cross sectional area and the condensation temperature. When each of the mass and the specific volume increases, the delivered negative increases. From the other hand, when the cross sectional area and the condensation temperature increase, the created vacuum decreases.
In the thermal power plant case, the condenser will have a constant condensation temperature, constant specific volume change and so cross sectional areas. This means that the created negative pressure depends mainly on the mass flow rate, and then the modeling equation can be rewritten;

$$\Delta P = -\, e^{C\dot{m}} \tag{20}$$

Where C is a constant that is expressed using the following equation;

$$C = \frac{(v_{gf}^2 + 2v_f v_{gf})}{ART} \tag{21}$$

The amount of steam or water to be recirculated to the TVP in order to control the vacuum can be calculated based on the following equation;

$$\Delta P_c = -\, e^{C(\dot{m}_t + \dot{m}_J)} \tag{22}$$

Considering constant mass flow rate at the steam turbine outlet, then the equation can be rewritten as follows;

$$\Delta P_c = -\, Ae^{C\dot{m}_J} \tag{23}$$

Where;

$$A = e^{C\dot{m}_t} \tag{24}$$

This equation shows that the vacuum to be maintained in the condenser is directly proportional to the TVP mass flow rate (to be injected).
The condenser sizing has an important role in assisting the TVP function. This can be expressed again in the equation;

$$C = \left(\frac{1}{RT}\right).\frac{(v_{gf}^2 + 2v_f v_{gf})}{A} \tag{25}$$

Some Design Considerations

There are some considerations that really impact the TV performance and must be taken into account in the modeling and design process. The first design consideration is the requirement of extra cooling capacity to condense the extra steam added on the condenser by thermo vacuum pump. In other words, if the TVP is placed in service the speed of the ACC fans must be increased in order to condense the extra mass of steam injected in

the condenser. The ACC unit will consume more power then. In addition, there might not be a sufficient cooling capacity designed for that, like the fans numbers or speed.
Conservation of energy equation provides that;

$$\dot{m}_s.h_{fg} = \varepsilon.\dot{m}_c.\Delta h_c \tag{26}$$

Then;

$$\dot{m}_c = \dot{m}_s \frac{h_{fg}}{\varepsilon.\Delta h_c} \tag{27}$$

This equation relates the required coolant mass flow rate at the ACC with the steam mass flow rate in order for the process to be balanced and controlled. The mass flow rate of the coolant depends on the speed ACC the fans. E.g. at summer the fans are mostly placed in service at high speed, so the cooling capacity can be only increased by the evaporation cooling (water injection) at the condenser external surface, which poses a loss in the water.

The second design consideration is the possible adverse effect on the cooling efficiency of the condenser. When the turbine exhaust vacuum increases, the pressure goes down hence the condensation temperature goes down as well. This follows that the temperature difference across the condenser will decrease and so the condenser cooling efficiency will drop down. In order to overcome this effect, the coolant mass flow rate needs to be increased in order to substitute this decrease in the driving force of the heat exchange. So TVP is a more attractive solution at the areas with more variation in the weather temperatures throughout the year.

The third consideration is the complexity of the water or steam injection control process. The injection at the condenser is a quite complex process. If the TVP is water - injection design. The injected water is evaporated once injected due to the adiabatic expansion. Figure 3 depicts some important aspects in the dynamics of the injection process. The spray characteristics are of great importance in order for the process to be effective. The spray tip penetration (L), cone angle (θ) and break up length (L') are mainly the governing factors. These characteristics are to be studied in further research in the future.

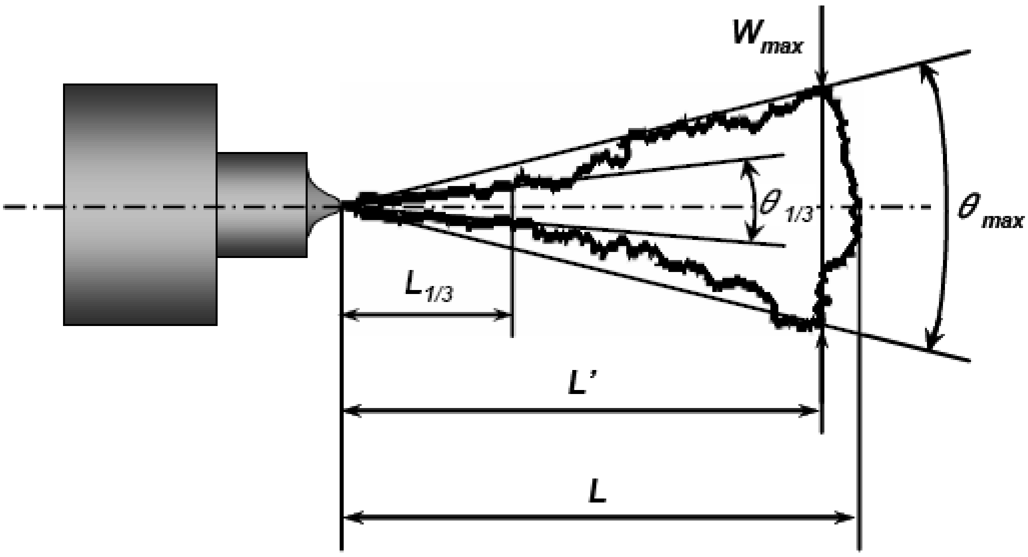

Figure 3 Spray penetration, spray angle and spray cone angle by Senda et al [8]

These factors control the integration of the injected liquid in the steam stream, which in turn controls the Vacuum Production Rate (VPR) throughout the control volume.

$$VPR = -\int \frac{dP}{dt} \tag{28}$$

The process is to be treated as a mixing flow process.
From the other hand, the Longitudinal Vacuum Growth (LVG) can be defined by;

$$LVG = -\frac{d\dot{P}}{dz} \tag{29}$$

The LVG determines the differential pressure profile through the condenser and so the dynamic characteristics of the flow, like the linear velocity and the drag force.
The Expansion Ratio (ER) also should be considered as one of the process considerations;

$$ER = \frac{v_1}{v_2} \qquad (29)$$

The distribution, and configuration, of the spray through the stream is important. The sprays distribution is an important factor because it affects the uniformity of the drag force profile through the cross sectional area, which is the Vacuum Uniformity.

$$VU = \frac{\left(\int_{A1}^{A2} d(\frac{f}{A})\right)}{f/(A_2 - A_1)} \qquad (30)$$

Where VU is the Vacuum Uniformity (Dimensionless), whereas VU goes to 1 at ideal process

The injection can be continuous or intermittent. The continuous injection poses better control over the process parameters.

The water has no effect on the resources sustainability because it is re-circulated inside the cycle. In the inverse, it promises to bring greater efficiency to the process, which means better resources exploit.

The fourth consideration is how the steam or water will be circulated and injected at the condenser inlet although the condenser is tightly sealed. In other words, if the condenser is connected with an environment with different pressure, the vacuum will not be maintained. The condenser is a huge body and if any leak or pressure change takes place somewhere then it will be difficult to control the pressure in such a huge system. In order to overcome this consideration, an ejector might be used to circulate the fluid. Another solution is the expansion of the fluid using nozzles after circulating the fluid with a pump. In addition, placing the TVP at the start up using an ejector and connecting it openly with the condenser and the condensate return tank can be a solution. The condensate can be circulated from the bottom of the condensate return tank and heated or the steam can be circulated from the top of it naturally to the condenser by means of the drag force of the condenser vacuum.

Finally, the economic feasibility of the TVP is a critical factor depends on some other factors. These factors are: The energy consumed in the injection pumps or the coolers (E_C), the energy produced by the thermo vacuum (E_p), the capital and O&M costs of providing thermo vacuum pump C_P, the other systems combined with the thermo vacuum pump (like the fogging), its feasibility (f_O), the energy sale prices (C_E), and the payback period of the invested money (n).

As for the engineering feasibility, if

$$E_p > E_c$$

Then it is feasible.

However, from the economic perspective other terms should be used to justify the feasibility.

Some experts argue [7] that 5 years is a good payback period to make the calculations. Assuming 5 years payback period, then the thermo vacuum pump will be feasible only if;

$$C_E \, of \, (E_p - E_c) - C_P + f_o \gg 0 \qquad (31)$$

In this formula, the only engineering term to control is $(E_p - E_c)$. This implies that, the most challengeable issue in thermo vacuum design is widen the gap between the energy produced and consumed, that is it will be feasible only if

$$E_p \gg E_c$$

In order to achieve this condition, the challenges are;

E_C Should be reduced as much as possible through utilizing thermodynamics techniques

E_P Should be maximized as possible through utilizing gas dynamics techniques to optimize the injection process and thermo fluids techniques to enhance the flow mixing process

E_C Has two main components, energy needed for water circulation and energy needed for water cooling, if any.

IV. Conclusion

Thermo Vacuum Pump (TVP) is a thermodynamic machine that delivers and controls the vacuum in a process by means of the phase change of a fluid. Thermo vacuum pump principle works toward creating the vacuum by controlling the condensation flow rate, condenser sizing, condenser shape, heat removal rate, and injected water, or steam, mass flow rate.

One important added value in the TVP principle is that it argues that the vacuum at the condenser can be increased and controlled by injecting water, or steam, in the condenser. Based on Euler equation and the ideal gas equation, the following equation has been derived so as to justify the TVP principle in theoretical terms,

$$\Delta P_c = -Ae^{C\dot{m}_J}$$

This equation shows that the vacuum to be maintained in the condenser is directly proportional to the TVP mass flow rate (mass to be injected).

TVP seems to be a promising opportunity to maximize the overall efficiency of the thermal power plants as the theoretical relationships provides. It increases the capacity of the steam turbine at winter because it allows increasing the condenser vacuum by drawing upon the condenser full capacity. From the other hand, it can assist to maximize the condensation efficiency at summer by taking advantage from the evaporation cooling through the water injection. Anyhow, TVP can also be integrated in each cycle in various ways so that the most can be made of the cycle energy losses making them into extra energy outputs rather than burdens. TVP can be combined with Gas Turbine fogging system, Feed Water Heaters or Gas Turbine inlet cooling system (e.g. HVAC). Heat and mass balance must be studied in each individual case thoroughly in order to decide how TVP must be incorporated into the cycle, if feasible.

A steam injection also can be a good solution if it is combined with a two direction heat exchanger for example. The heat exchanger in this case either reheats the saturated steam in order to inject it into the low pressure turbine or, in other side, reheats the saturated water in order to inject in the condenser. This scenario seems to be theoretically feasible but it has to be justified by a separate study.

To prove to be economically feasible, TVP must bring considerable savings in the specific energy input costs that makes the payback period of its capital cost less than five years. Therefore, the energy tariff, TVP O&M costs, and some other business environment related factors must be taken into account when the TVP installation is to be studied.

The most critical technical success factor in the TVP is the flow mixing process, where the spray characteristics, the injection points, injection pattern, injectors distribution and some other factors must be studied. A further research is required to be made about these factors and how they are going to affect the process control. The simulation of different scenarios as well as special practical experiments is both needed to confirm and validate the theoretical results.

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ACKNOWLEDGMENT

I present this work to my mother and wife.

NOMENCLATURE

$-\Delta P$	negative static pressure created due to the phase change, pa
$\dot{m}$	the mass flow rate of the gas to be condensed, kg/s
ΔV	the change in the volume that results from the phase change, m3
m	the mass that is condensing, kg
ρ_g	the density of the steam, kg/m3
ρ_l	the density of the water, kg/m3
v_g	the specific volume of the steam, m3/kg
v_f	the specific volume of the water, m3/kg

v_{gf}	$(v_f - v_g)$
$\dot{m}_t$	The process mass flow rate without the TVP, or the turbine outlet mass flow rate (kg/s)
R	The gas constant, pa.m3/kg.k
ΔP_c	The vacuum to be maintained, or the control vacuum
A	The cross sectional area (m^3)
$\dot{m}_J$	The mass flow rate to be injected in order to maintain the control vacuum ΔP_c, (kg/s)
T	The temperature degree at which the condensation takes place, k
F	The drag force (n).

Figure Captions List

Fig. 1	How vacuum is created by the thermo vacuum pump (Considered as a Sink of mass)
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Fig. 4	A simple model of thermo vacuum pump
Fig. 5	Simple representation of a steam cycle plant with TWO FWH's before utilizing the thermo vacuum pump. F1 is the FWH 1 and F2 represents FWH2
Fig. 6	Figure 6 simple representation of a steam cycle with two FWH's after utilizing thermo vacuum pump. F1 is the FWH 1 while F2 represents FWH2.

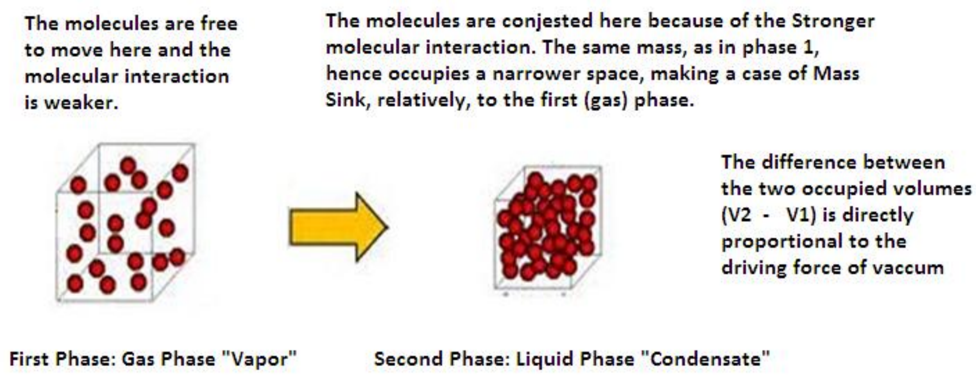

Figure 1 how vacuum is created by the thermo vacuum pump (Considered as a Sink of mass)

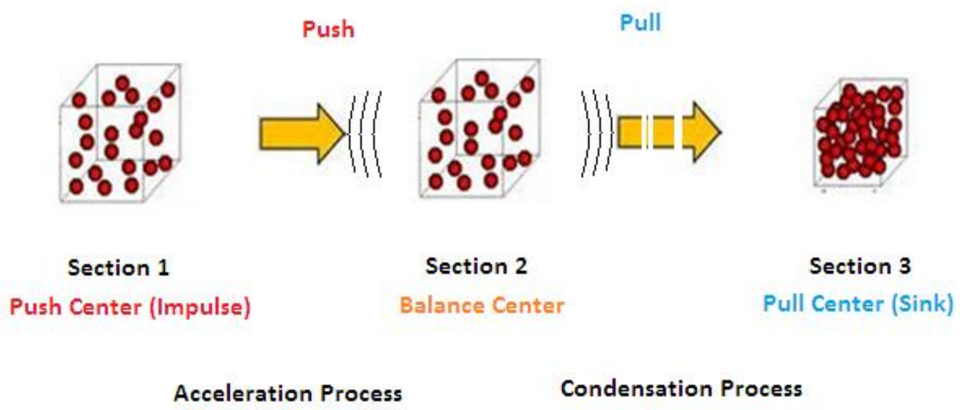

Figure 2 Three differential sections where the condensation takes place

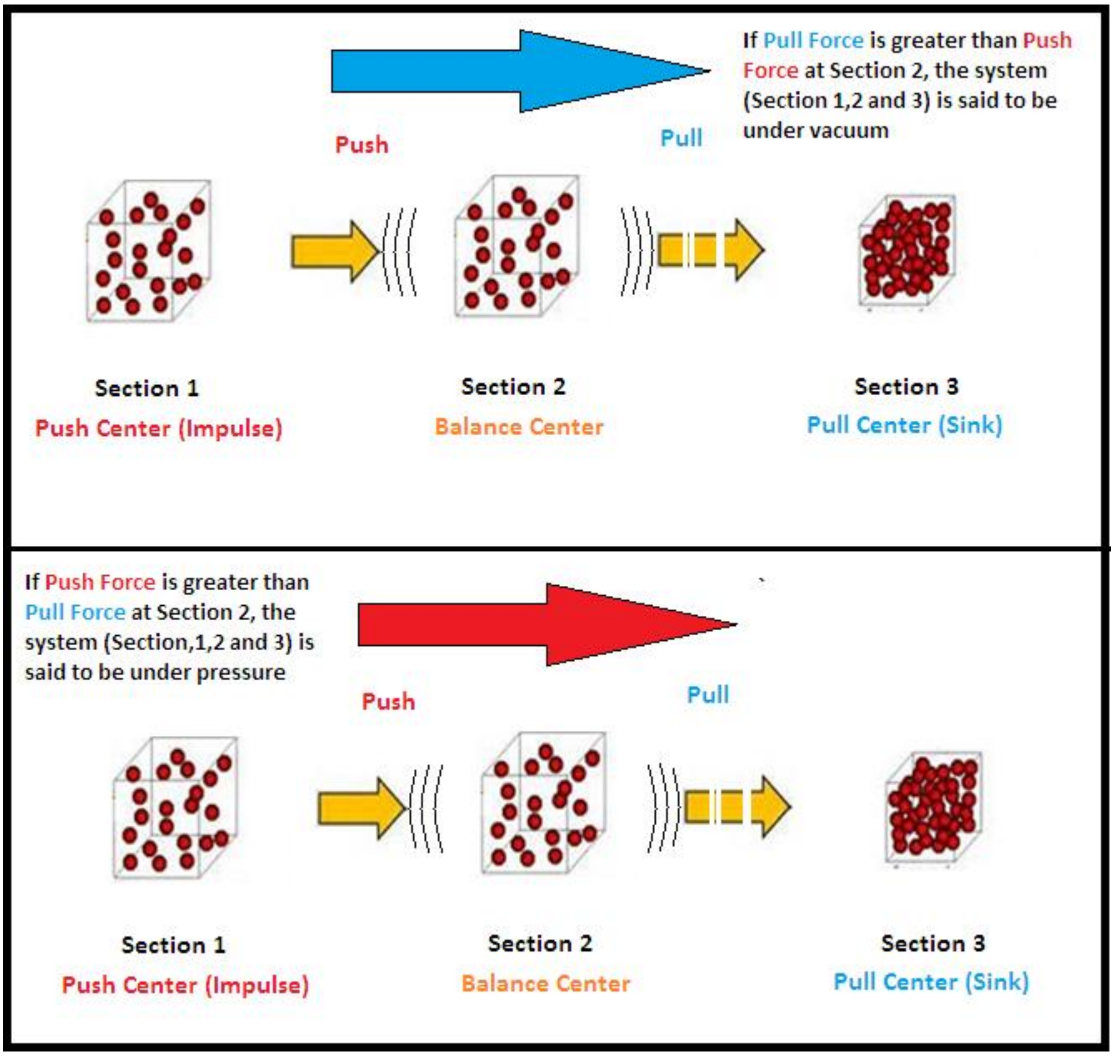

Figure 3 How the Vacuum and Pressure are defined based on a differential point of view

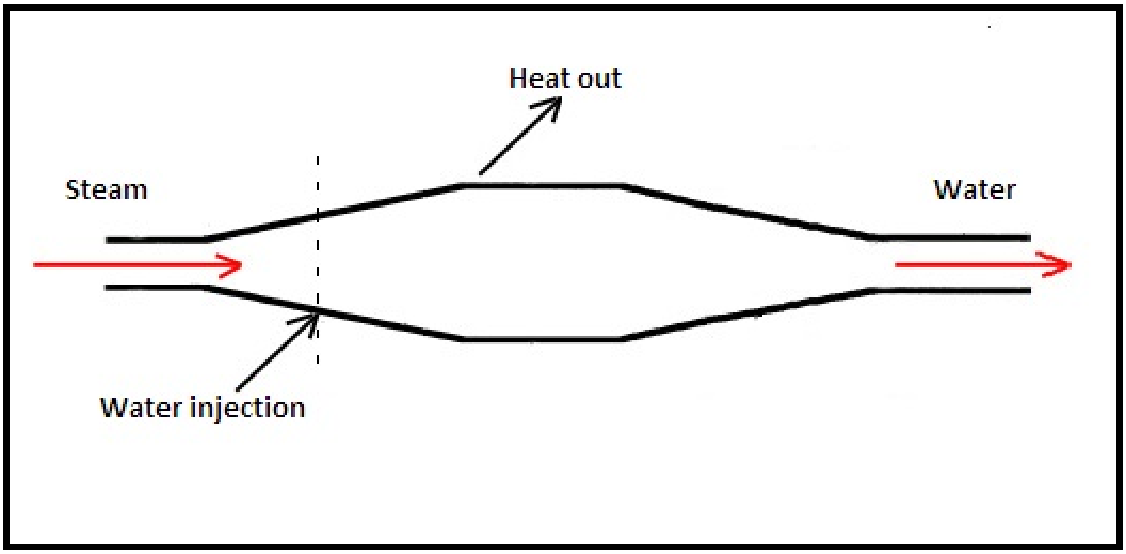

Figure 4 A simple model of thermo vacuum pump

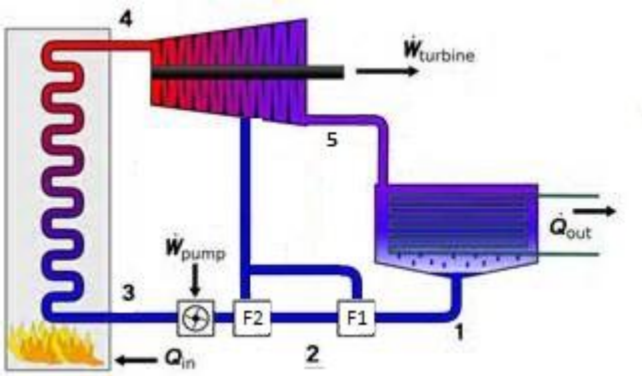

Figure 5 simple representation of a steam cycle plant with TWO FWH's before utilizing the thermo vacuum pump. F1 is the FWH 1 and F2 represents FWH2.

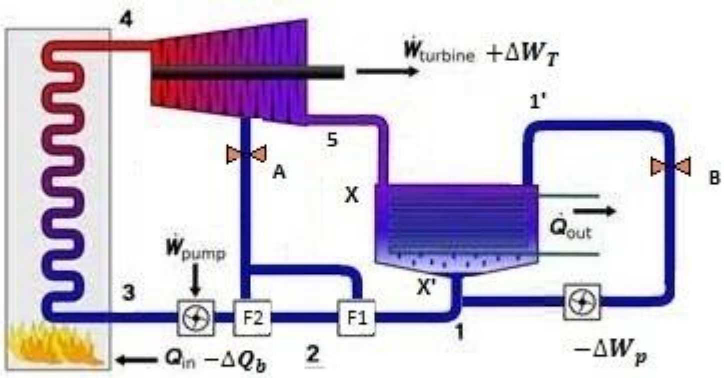

Figure 6 simple representation of a steam cycle with two FWH's after utilizing thermo vacuum pump. F1 is the FWH 1 and FWH 2, while F2 represents the FWH3, FWH4 and FWH5.

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