Proceedings of COBEM 2009
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20th International Congress of Mechanical Engineering
November 15-20, 2009, Gramado, RS, Brazil

THERMAL ANALYSIS OF A DISTILLATION UNIT AIDED BY A VAPOR CHAMBER AND NON-CONDENSIBLE GAS

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Abstract. *A significant portion of oils extracted from Brazil fields could be considered extra-heavy. Then comes the need to innovate the technologies of extraction, to obtain the extra-heavy oil which extraction be economically viable. The insertion of a diluent directly inside the well to reduce the viscosity and density of this oil, and by that reducing the cost of extracting the petroleum is already happening in on-shore wells of others countries. However, this practice is not economically viable in off-shore wells, because the cost and environmental risk due to a constant transmission of diluent for the platform. Thus came the idea of obtaining the diluent still on the seas, from the extra-heavy oil, with a compact and economical distillation unit. One proposal under study, is a distillery that has a novel configuration and is aided by a vapor chamber. The objective of this work is the study and development of a thermal control system of a distillation unit, based on film evaporation, aided by a vapor chamber. Preliminary studies showed that a longitudinal variation in the temperature of the wall helps to reduce the height of the column, and also the energy efficiency of the device. To obtain a temperature profile that meets this configuration it introduces an amount of non condensable gas inside the vapor chamber. A simplified mathematical model was proposed to estimate the longitudinal profile of temperature within the vapor chamber for different powers applied to the system. Additionally, a model of condensation when the wall temperature varies in the presence of non-condensable gases, is proposed. A simplified prototype of glass is under construction for the display of the two-phase phenomenon of heat transfer that occurs within the vapor chamber, and to assess the results of the mathematical model.*

Keywords*: Two-Phase Thermosyphons , Vapor Chamber, Non-Condensible Gas, Distillation*

1. INTRODUCTION

With the intention to extract extra heavy oils more efficiently, came the idea to insert, directly to the oil well, a diluent with light hydrocarbon chain, to reduce the viscosity and density of the oil, making its extraction economically viable.

However, the transport of this diluent, mainly to offshore oil wells, is logistically difficult and sets a very high environmental risk. One idea to solve this problem is to obtain this diluent from the extra-heavy oil at the offshore well, and insert this oil to the well, product dilute *oil – synthetic oil*, distil the synthetic oil to re-obtain the dilute light fraction, and re-cycle this fraction to the well. Therefore, a device which employs low amount of energy, of low cost and with low volume and high is desirable due to the constraints of exploring platforms.

A distillation unit under investigation employs the falling film distillation technology. In a few words, a falling film distillation unit consists of a heated channel by which surface a thin film of raw oil descends. According to the temperature of the wall, the most volatile components of the oil evaporate and moves up to the top of the channel in the center region. In this way, the distillation separates basically two components of the oil, the crude and the dilute oils. Preliminary studies showed that a suitable and controllable temperature profile over the wall can reduce the energy waste of the device and the height of the channel. Therefore, a device designed to promote the falling film distillation should include a temperature profile controlled wall.

Two phase thermosyphons are devices with high thermal conductivity that can transfer high quantities of heat. A conventional thermosyphon is a hollow evacuated metal pipe, charged with a pre-determined amount of an appropriate working fluid. It can be divided into three main sections: evaporator, where the heat is delivered to the device, an adiabatic section and a condenser, where the heat is released. The heat causes the evaporation of the working fluid resulting the vapor that goes towards the condenser region by means of pressure gradients, where it condenses, returning to the evaporator by gravity. The difference between the loop thermosyphon to a conventional thermosyphon is the splitting of the adiabatic section in two ducts: one to the transport of vapor and another to the return of the condensate working fluid. This configuration have two advantages over to the conventional thermosyphon: the separation of the liquid and the vapor phase flows, avoiding the undesirable drag effect, which can reduce the efficiency of the device. Also, it allows for more flexible condenser geometry, which can be useful in applications where the conventional configuration can not be used. Figure 1 shows both the conventional (a) and the loop thermosyphon (b).

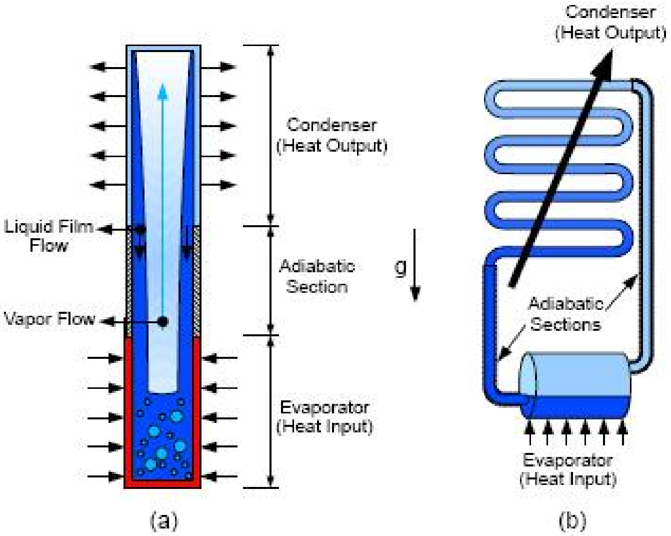

Fig. 1 –Conventional two-phase thermosyphon (a) and the two-phase loop thermosyphon (b).

In the present research, vapor chamber thermosyphon technology is being considered to promote the controlled temperature profile necessary to the falling film distillation process. The main idea is mix vapor and non condensable gases in the condenser region of a cylindrical shaped vapor chamber, with the objective of controlling the temperature profile. To design such devices, analytical models are powerful tools which need to be developed. Therefore, the objective of the present work is to present an analytical one-dimensional model of the condenser, where the Fick's law is employed to estimate the longitudinal concentration of the steam and non-condensible gases along the cylindrical tube. The saturated steam hypothesis is applied to predict the mean temperature of the condenser wall.

3. THE DISTILLATION DEVICE

A two phase loop thermosyphon apparatus was designed for the distillation channel of a falling film distillation unit, as shown in Fig. 2. The vapor is also responsible to deliver the necessary heat to the distillation process. In this case, the condenser can also de denominated as vapor chamber. As it is well known, the longitudinal temperature profile of the condenser in a two-phase thermosyphon is basically constant, without a variation of the temperature as wished in the present case. To induce this variation, a non-condensible gas reservoir is introduced at the condenser top, as illustrated in Fig. 2. The non condensable gas diffuses through the vapor, modifying the longitudinal profile of the wall temperature along of the distillation channel.

Heat is applied in the evaporator and vapor is generated. The vapor moves, by density difference, in the direction of the vapor chamber. In the center of the vapor chamber there is the distillation cylinder, in which inside wall the liquid to be distillated falls in a thin film and, therefore, absorbs part of the heat transported by the vapor. The vapor in contact with the wall condensates and the resulting fluid is conducted to the vapor chamber bottom region, returning to the evaporator. The temperature profile over the distillation wall is obtained by the controlled release of non condensable gases stored in the gas reservoir.

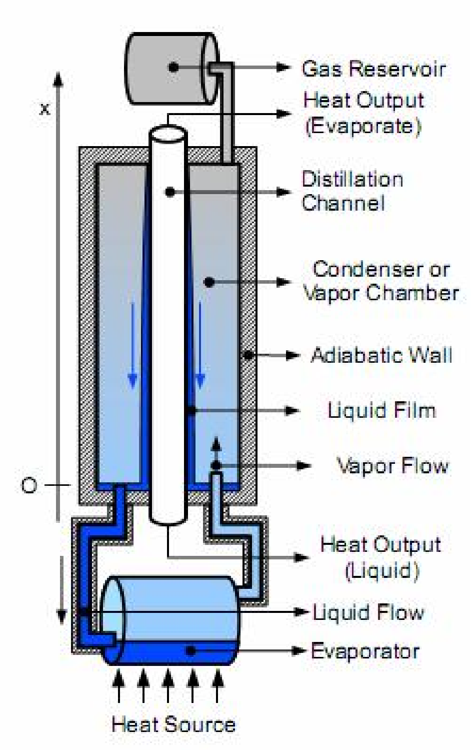

Figure 2. Scheme of the distillation device.

4. THE ANALITYCAL MODEL

It is expected that the temperature profile is directly related to the concentration profile in the condenser. Rohani and Tien (1973) suggest a two-dimensional model to predict the longitudinal concentration profile, in cylindrical coordinates, where the radial direction profile is also taken into account. In the present work, a one one-dimensional diffusion model condenser is proposed for the condenser, as the geometry of the device suggests that this could be a reasonable approximation. The vapor is considered saturated. Natural convection effects due to the temperature stratification of the non-condensible gas at the top region of the condenser are neglected. Therefore, the molar transport equation, of vapor mixed with the non-condensible gas, which is considered stagnant in the condenser, is, according to Bejan (2008), the Fick's Law to a binary solution:

$$u(x)\frac{dC}{dx} = D_{ij}\frac{d^2C}{dx^2} \tag{1}$$

where *u* is the velocity of the vapor, which varies along of the height of the condenser, *D* the molar diffusion coefficient and *C* is the molar concentration of the vapor. A linear function is a good approximation for the vapor velocity, as it is reasonably to suppose that the condensation rate along of the condenser is a constant. Hence:

$$u(x) = -ax + b \tag{2}$$

To find the coefficients *a* and *b*, is needed prescribe the velocity at $x = 0$, and where the speed of the vapor entering the chamber is known

$$u_{in} = \frac{\dot{q}}{h_{lv}\rho_{vap}A}, \tag{3}$$

where $\dot{q}$ is the heat power applied to the evaporator, h_{lv} the latent heat of vaporization, ρ_{vap} the vapor density, and A is the cross-section area of the condenser. According to Angelo (2007), there is a significant accumulation of the non-condensible gases at the end of the condenser and almost no vapor in this region, especially in its saturated state. The effective length of condenser, defined as the total length minus the length blocked by the non-condensable gases, can be determined experimentally, applying the following flat front model proposed by Edwards and Marcus (1970) *apud* Faghri (1995):

$$L_{ef} = L_C - \frac{m_g R_g T_{g,i}}{p_{g,i} A} \tag{4}$$

where L_c is the condenser length, m_g mass of non-condensible gas, R_g the gas constant of the gas, $T_{g,i}$ the interfacial gas-vapor temperature and $p_{g,i}$ the partial pressure of non-condensible gas at the interface.

In this region, it is reasonable to suppose that the velocity of vapor is null. Therefore:

$$u(L_{ef}) = 0 \tag{5}$$

Then, the longitudinal velocity of the vapor can be written as:

$$u(x) = -\frac{\dot{q}}{h_{lv}\rho_{vap}A}\frac{x}{L_{ef}} + \frac{\dot{q}}{h_{lv}\rho_{vap}A} \tag{6}$$

The boundary conditions are:

At $x = 0 \quad : \quad C = C_{sat}(T_i)$ (7a)

At $x = L_{ef} \quad : \quad C = C_{sat}(T_{gnc})$ (7b)

where C_{sat} is the concentration of the saturated vapor at the temperature of evaporator (T_i) and at the temperature of non-condensible gas (T_{gnc}). Such values can be obtained by a thermodynamic table for the vapor.

The solution of Eq. 1 can be written in terms of the function error. With the aid of the software EES (Engineering Equation Solver), the boundary conditions was determined and the analytical solution was implemented to obtain the vapor concentration and its temperature using the saturation condition.

Below in the Table 1, the values of the parameters and physical properties used to obtain the result.

Table 1. Values of the parameters and physical properties.

D (m²/s)	Ti(ºC)	Tgnc(ºC)	A(m²)	Lc(m)
1,0 x 10^{-5}	97,0	70,0	2,61 x 10^{-3}	1,00

The mass diffusivity was estimated by the Chapman-Enskog correlation (Cremasco, 2002). Figure 3 shows the axial density profile of saturated vapor obtained to four magnitudes of applied heat power.

With the density values, and using the saturated vapor hypothesis, is possible to obtain the profile of mean temperature of the condenser, using a thermodynamic table. In Fig. 4, is possible to see that, as the heat power increases, the temperature distribution tends to be constant with a sharp decrease to the temperature of the non-condensible gas. It happens because the vapor “pushes” the non-condensible gas to the top of the condenser, due the high velocity, which is a consequence of the higher power inputs applied. In this level, the velocity of vapor is shown to be high enough to overcome neglect the diffusive effects between vapor and gas. On the other hand, for lower levels of power inputs, the diffusion effects can be more pronounced, causing a smooth transition between the inside wall temperature and the non-condensable gas temperature.

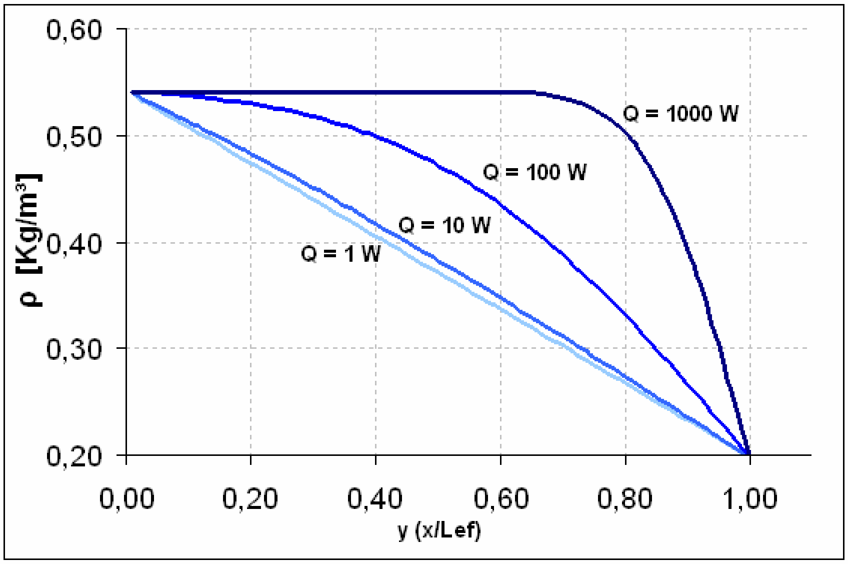

Figure 3. Density distribution along of the condenser.

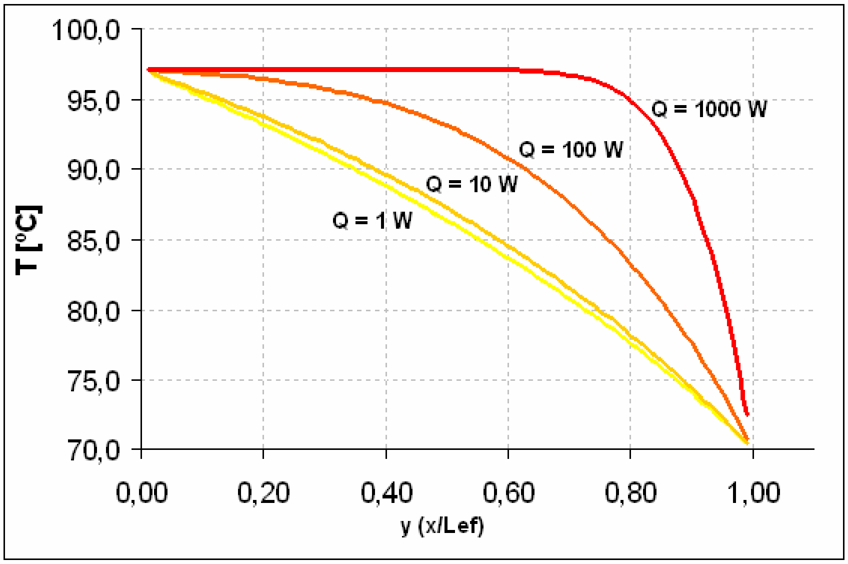

Figure 4. Temperature profile of vapor along of the condenser.

5. CONCLUSIONS

In the present work, a one dimensional model of the gaseous diffusion of non condensable gas in vapor was presented, to predict the density and temperature profile of the condenser of a two-phase loop thermosyphon. The preliminary results presented in this paper show the potentiality of using the technology of vapor chamber with a mixture of vapor and a non condensable gas to control the temperature profile of a tube inside where distillation may happen. This is a new technology which may end in compact, well controlled low const equipment, which could be used inside oil platforms in ocean.

A one-dimensional energy balance of the wall is under study to estimate, with a good approximation, the condenser phenomena. Also, an experimental apparatus is under construction to validate the theoretical model.

This work is under development in the context of a project financed by Petrobras, developed together with the LCP, the Laboratory of Control of Processes of the Chemical Engineering Department of the Federal University of Santa Catarina (UFSC). The LCP laboratory is analyzing the hydrodynamic behavior of the descending film, as well as other relevant distillation phenomena.

7. ACKNOWLEDGEMENTS

The authors express their appreciation to the PETROBRAS, the Brazilian Petroleum Company, and the Department of Mechanical Engineering (EMC) of the Federal University of Santa Catarina (UFSC) and CNPq for scholarship.

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