CONCEPTION OF A TEST CONDENSATION EXPERIMENT APPARATUS

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Abstract. *An experimental apparatus has been designed to determine the effect of the presence of noncondensable gases in vapor at atmospheric pressure in the condensation process of vertical and inclined cooled surfaces in filmwise condensation mode. The heat transfer rates are measured by the cooling water system by means of the mass flow and the inlet and outlet colling water temperatures. The mass of collected condensate times the latent heat of vaporization can also be used to evaluate the heat transferred. The overall heat transfer coefficients may be obtained in several different conditions such as sub-cooling levels, plate inclinations and orientations, Reynolds number of the steam/gas mixture flow and different concetrations of air. Also, different condensing surfaces can be studied such as: plain, grooved and porous medium over a flat and grooved substract. The resulting data from this apparatus can be used to be compered with models and correlations.*

Keywords*: Filmwise Condensation, Flat Plate, Noncondensable Gases, Inclined Surfaces*

1. INTRODUCTION

Condensation processes can be applied in a variety of engineering industrial and domestic applications, such as air dryers, heat transfer devices, water recovery in cooling towers, etc. Therefore, the heat transfer mechanisms, as well as the condensate film formation induced by condensation phenomena, have attracted a lot of research interest. Since the first work in the field of theoretical analysis of filmwise condensation developed by Nusselt em 1916, a number of workers such as Rohsenow [1], Sparrow and Gregg [2], Chen [3] and others have improved Nusselt's model, by removing some of the original highly restrictive assumptions.

Dropwise condensation has received attention due to its higher heat transfer coefficients when compared with the filmwise condensation. The main problem of this mode of condensation is related to the difficulty of keeping the drops for a long time. After the drops start to fall, the surface becomes wet and the drops have problems in emerging again. Many authors have directed their researches to the development of new coating materials, different kind of substrates or other deposition methods, in order to provide a surface with poor wetability better characteristics and though obtain dropwise condensation for a longer period [4-8].

Although it is desirable to achieve dropwise condensation for industrial applications, it is often difficult to maintain these conditions. For this reason, porous medium in the filmwise condensation also has gained attention from the researchers [9-15]. According to Wang et al. [16], who studied the condensation over a wavy surface covered by a porous medium, significant enhancement in the heat transfer can be reached with the increase of the waviness, due to the increase of the contact area. Although they did not considered the effects of capillary forces induced by the porous medium, Tong-Bou Chang [17] showed that the porous media effectively enhances the heat transfer performance of the surface. All the researchers mentioned before conducted theoretical works using the conservation equations in the formulation of the problem. Not many works concerning experimental data of condensation of flat surfaces covered by a porous material are available in the literature.

It is well know that the presence of noncondensable gases in vapor reduces drastically the condensation heat transfer process and the condensations rates, even if with a small amount of gases. Bum-Jin et al. [18] and Xue-Hu Ma [19] compared filmwise and dropwise condensation of water in a vertical flat plate with the presence of noncondensable gases (air) over a range of 0 to 6% of air mass fraction. They verified that the effect the noncondensable gases are different for each mode of condensation. The interfacial dynamic of dropwise is different from the filmwise condensation; actually the liquid boundary condition help the destruction of the gas boundary layer and so improves the heat transfer process. The effect of noncondensable gases can be decreased by increasing the liquid film Reynolds number, so that the liquid film interface becomes wavy (transition from laminar to turbulent flow). Further increase of Reynolds number turns the and later liquid film turbulent. Park et al. [20] conducted a series of experiments of filmwise condensation over a vertical flat plate in the presence of noncondensable gases in the wavy flow region. According to them, for a given air-mass fraction and a vapor-gas mixture velocity, the overall heat transfer increase with the increment of the liquid film Reynolds number. Moreover, A. M. Zhu et al. [21] studied the effect of high amounts of noncondensable gases in the vapor on the condensation over a variety of vertical tube lengths. One of their results is that, as the Reynolds number of the mixture increases, the effect of the noncondensable gases in the condensation decreases. According to these authors, the gas boundary layer is destroyed by the mixture velocity, so that the vapor can reach the surface and condense easily.

As exposed above, most of the researchers devoted their work to vertical or horizontal flat plates or pipes. Just a few authors treated the condensation in the underside of horizontal flat plate and with some different inclination angles [22-23]. So, this paper presents the conception of an experimental apparatus developed to study the physics involved in the filmwise condensation, with or without the presence of noncondensable gases, on flat and grooved surfaces, with or without porous medium layer deposited over a flat and grooved substrate, on a variety of inclination angles. This device will also provide data to be used for the comparison with new analytical expressions or numerical investigations of the condensation phenomena, including the film thickness, condensate mass flow rate and heat transfer coefficients.

2. EXPERIMENTAL FACILITY

As already mentioned, the experimental facility must be designed to allow the study of the condensation of cooled surfaces subjected to a controlled mixture of noncondensable gases and vapor, in terms of mass flux and composition. Several different surfaces, with different surface conditions, materials and surface finishing (grooves, deposition of porous media, etc) will be tested, under different inclinations, temperatures, etc. The experimental facility developed in this work consists of a test section and auxiliary equipments, such as: steam generator, cooling water system, noncondensable gases supplier and data acquisition system, which are grouped in three main sections: boiler, vapor supply line and test section.

All parts of the test equipment are properly insulated in order to avoid considerable energy losses to the surroundings.

2.1. Boiler

The boiler consists of a container were water is heated up to its vaporization. It was designed with galvanized carbon steel with 2 mm of thickness and with 600x500x270 mm of lengths. The heating is provided by means of electrical heaters. The delivered heat power is controlled by means of four modules, with three electrical heaters, which can be individually controlled (on or off). Each module is able to deliver 7.5 kW. The control of power level is achieved by means of a Variac, which is connected to the heaters. A level gauge is used to identify the level of water inside the boiler and a rotameter is able to measure the volume flow rate of the inlet water supplied. Figure 1 shows the schematic of this part of the device.

The main purpose of the boiler is to produce and deliver a controlled amount of steam, which reaches the downward condensation surface to be tested. By means of the level gauge and the rotameter, the mass flow rate of steam can be known. The apparatus is open to the atmosphere and, therefore, the steam temperature is equivalent to the saturation temperature at atmospheric pressure.

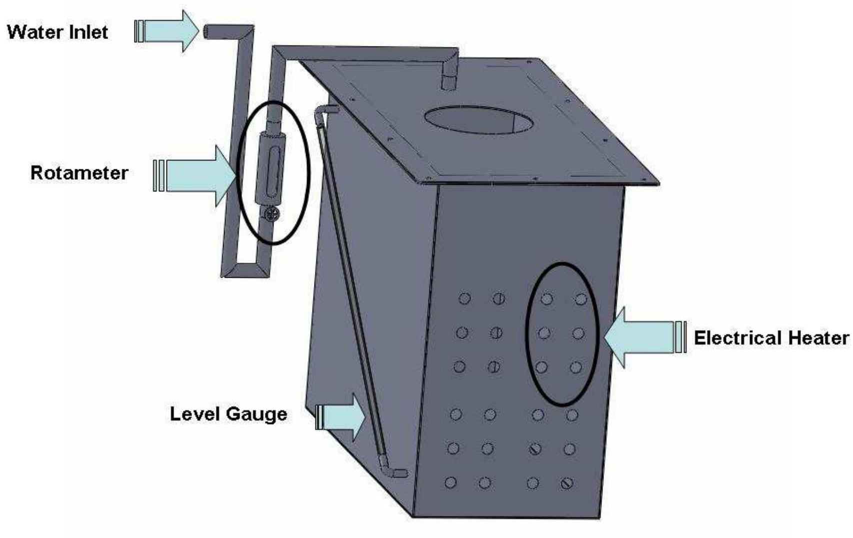

Figure 1. Schematic of the boiler

2.2. Vapor Supply Line

The vapor supply line consists of a main cylindrical column and a smaller square section duct. Both these ducts were projected with galvanized carbon steel with 2 mm of thickness. The main column has 147 mm of inner-diameter and 1000 mm of height, whereas the square duct has 50 mm cross section internal side and 300 mm of length.

The square duct, which is connected to the column, is in charge to deliver the controlled amount of noncondensable gases to the equipment. The noncondensable gas employed is the atmospheric air, which is introduced to the main cylinder by means of an air blower. Inside this duct there is an electrical heater. Knowing the power supplied to the air and its thermal capacity, the mass flow rate can be obtained through the difference of dry bulb temperature from the thermocouples before and after the electrical heater. Besides, the air flow is measured and is deliveredto the equipment at same temperature of the steam generated by the boiler, so that the water vapor keeps its dry saturated condition. Even if the literature states that the amount of vapor in dry air is negligible, in this experimental setup, the humidity of the air is checked before reaching the cylindrical column in order to know exactly the ratio of air and vapor delivered for testing.

The main column receives the generated steam from the boiler located in the bottom, which dry bulb temperature is . A checked by a thermocoupleJust after the steam inlet, the noncondensable gases are introduced and mixed with the vapor, in a controlled proportion. In the top of this column, there is a rectifier which organizes velocity profile of the air and vapor mixture and helps in the homogenization of the stream.

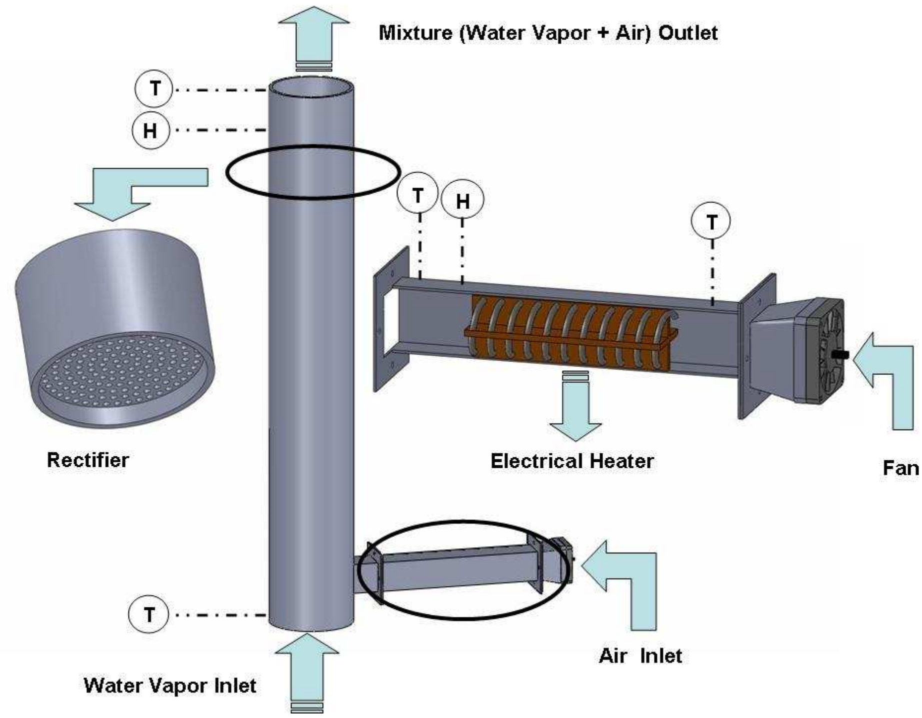

Figure 2. Schematic of the vapor and air supply line.

As the apparatus is insulated and no energy is lost to the environment, one can consider that no vapor is condensed while the vapor and air mixture moves through the cylinder. As the vapor and the air mass flows are known, the mixture velocity can be determined using the conservation of mass equation.

2.3. Test Section

The schematic of the test section is shown in Figure 3. The mixture composed by vapor and air comes from the bottom of the vapor supply cylinder and leaves its top opening, reaching the studied surface. The testing surface is installed over the lower side of a small heat exchanger, made by a hollow metallic parallelepiped box. Inside this box, cooling water circulates at rates and temperatures controlled, so that the amount of heat removed inside the box is known. As the surface is cooled, condensation happens in its face. As this cooling surface is not in horizontal position, the resulting condensate is collected in a drain by means of gravity. The residual mixture flows through the lateral gaps (between the tested surface and the test section vertical walls) and reaches the environment at the box top.

Two vertical glass walls are provided to the text section box to allow the visualization of the condensation phenomena over the tested surfaces. The other walls are made by galvanized carbon steel with 2 mm of thickness. The small heat exchanger, test surface and the insulation are fixed by their sides on the metallic walls of the test section, allowing the variations of the slopes.

The heat exchanger cooling water is provided by a water cooling bath which removes the latent heat released by the surface condensation process and keeps the device at the controlled temperature level, allowing the study of the influence of sub-cooling temperature levels in the condensation. The mass flux of this cooling water is measured by a rotameter. Seven thermocouples, connected to the data acquisition system, are designed to be embedded below the condensing surface in order to measure the surface temperatures.

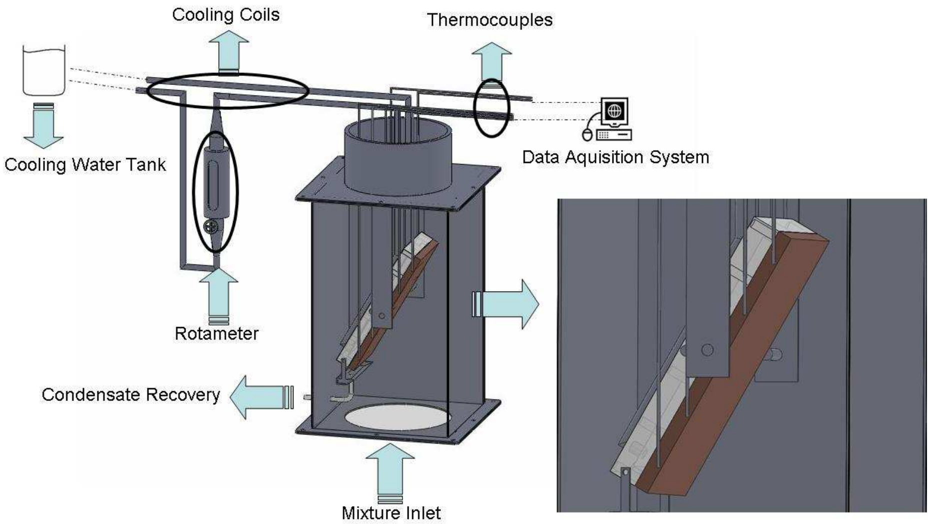

Figure 3 Schematic of the test section

Figure 4 shows the condensation surfaces to be tested. All the surfaces are rectangular and planar, with 10 mm of thickness and 100 mm of horizontal length. As already mentioned and shown in Fig. 3, the surfaces are tested under different inclinations. To keep the same gap area of vapor and air mixture passage between the sample edges and the lateral test section walls, the height of the condensing surfaces must change, according to the tested inclination. The first four flat surfaces shown in Fig. 4, from left to the right, have 106.4, 116.2, 142.8 and 200 mm of height, respectively and they are made of flat cooper. The other five have the same dimensions: 200 x 100 x 10 mm. The fourth surface is also flat and made by aluminum,while the last three surfaces are made by cooper. The sixth surface has longitudinal grooves; the seventh has a porous layer made of a sintered deposit of copper powder of 10 mm thickness. The last one has this same porous layer deposited over a grooved surface. The insulation, made of Nylon, has 10 mm of thickness.

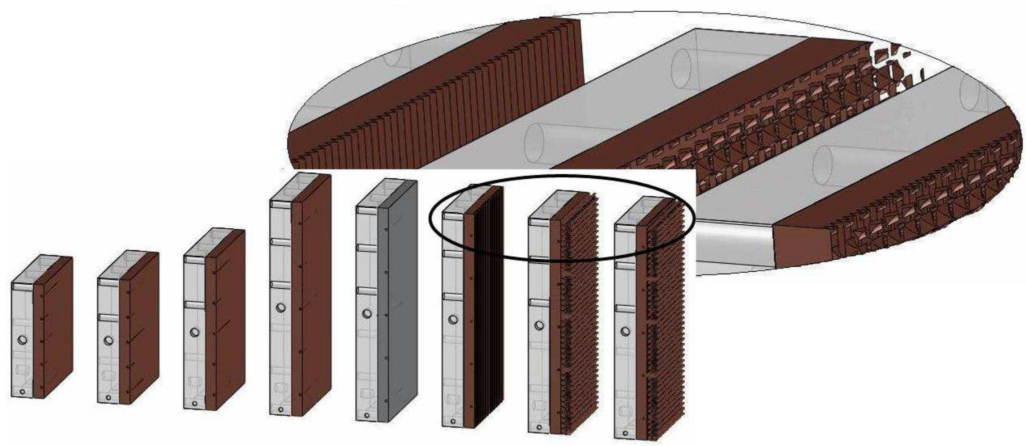

Figure 4 Schematic of the testes surfaces.

According to some results from the literature [22 and 23] systematic reductions of the heat transfer in condensation process are observed as the angle from the horizontal reduces, for condensation occurring in the downward surfaces. But, in these works, they used the same surface under different inclination angles, so that the projected area relative to the vapor and air mass flux were not the same. In other words, the amount of vapor or vapor and noncondensable gases mixture reaching the surface of the plate are not the same. Therefore the comparison among different inclination angles and the conclusions about the effectiveness of the surface as a vapor condenser are notconsistent. Thus, in the present work, in order to clarify this point, the variation of the angles is followed by different lengths of the surfaces, so that the projected area is the same, for all the tests and consequently it is expected that the same mass flow reaches the tested surfaces.

Figure 5 shows the complete set up mounted (composed by the boiler, vapor supply line and test section) ready for testing.

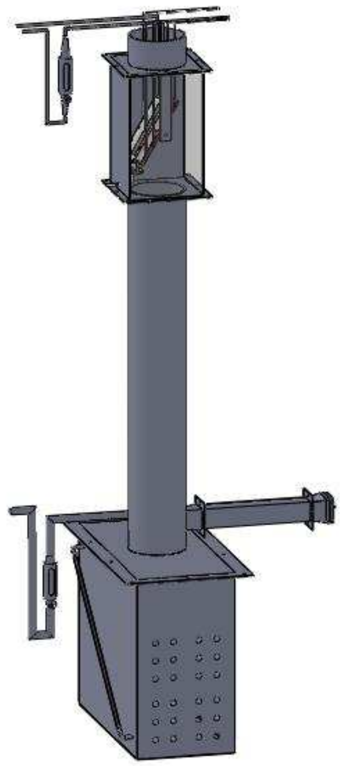

Figure 5 Schematic of the experimental apparatus

3. HEAT TRASNFER MEASUREMENT

The main objective of the surfaces under investigation is to condensate as much vapor present in a mixture of air and vapor as possible. Actually, the condensate is possible due to the removal of the heat from the vapor. As already described, the cooling water delivered to the heat exchange by means of a pump is kept at a constant temperature using a thermal bath. . As observed from Fig. 2, the inlet and outlet temperatures of the cooling water are measured as well as the vapor volume flow rate through a rotameter. Therefore, the heat removed from the condensation plate by the water can be determined by the equation:

$$Q_{water} = m_{water} c_p \left(T_{out} - T_{in}\right) \tag{1}$$

Where m_{water} is the mass of water, c_p is the specific heat of the water and Tout and Tin the inlet and outlet temperatureas of the water. Another way to check this amount of heat delivered to the surface is through the liquid condensated by the plate. Therefore, the latent heat removed can be determined by:

$$Q_{condensate} = m_{condensate} h_{vl} \tag{2}$$

where $m_{condensate}$ and h_{vl} are the condensate liquid collected from the condensing plate and the latent heat of water, respectively. The hypothesis of vapor in its saturated state is adopted (actually this is a fairly good hypothesis). According to [5] and [6], the heat balances obtained by these two methods agrees to within 10%. Therefore, the heat transfer data can be considered precise enough to be compared with analytical expressions or correlations developed from experimental and numerical investigations.

4. CONCLUSION

The conception of an experimental apparatus was idealized to test new surfaces in order to enhance the condensation heat transfer in the filmwise mode in downward position and to improve the understanding of the effects of noncondensable gases over new designed condensation surfaces. The flexibility of the apparatus allows the study of a number of effects such as plate inclination, mass concentration of air to steam, flow, variation of the Reynolds number of the mixture and sub-cooling of the surface temperature. This knowledge will give useful information for heat transfer engineers to design and construct heat air dryers or water recovering systems in cooling towers for industrial plants, among many other applications.

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