Frost formation around a vertical cylinder in humid air

Martins, Karlos Roberto da Silva Braga, karlos@fem.unicamp.br
Ismail, Kamal Abdel Radi, kamal@fem.unicamp.br
State University of Campinas, Faculty of Mechanical Engineering,
Cidade Universitária, Barão Geraldo, Campinas – SP, Brasil
13083-970, Caixa Postal 6122
Phone: 55 19 3521 3376

Abstract. *Formation of frost on cold surfaces provokes major operational and energetic difficulties in many engineering applications and equipments. In this paper an experimental was realized to establish the effect of varying the operational parameters on the frost formation. Results of the effect of varying the humid air mass flow rate on the velocity of frost deposition, thickness of the frost layer and angular distribution of the frost layer are presented and discussed.*

Keywords: *Formation of frost, deposition velocity, frost thickness. frost*

1. INTRODUCTION

The formation of frost on cold surfaces is considered as a problem in many applications of industrial and commercial interest such as evaporators, condenser and many other application. The formation of frost is usually associated with increase in the thermal resistance and hence bad heat transfer to or from the frosted surface associated with large pressure drop and low air flow. The solution in this case is to remove the frost formed by mechanical scrubbing a process which is not adequate for situations and equipments. The other way is by thermal action though a thermal shock by reversing the system operation and making the hot gas to flow through the frosted tubes. This method has the disadvantage of introducing heat in the ambient required to be cold. Another possible way is to use heat bars placed in between the tube arrays and by switching them on, the frost is melted and removed.

A literature survey revealed some relevant papers to the subject, of which one by Chung and Agren [1] where they presented an experimental and theoretical study on the formation of frost around a vertical cylinder. In their study they used a steady state model to predict the thickness of the frost layer. Later Niederer [2] studied the influence of the frost formation on the heat transfer and associated energy losses. The study realized by Yonko and Sepsy [3] was devoted to evaluate experimentally the thermal conductivity of the frost in terms of its density and effects of the air velocity and surface temperature on the layer of deposited frost, its density and thermal conductivity. Hayashi [4] and Tokura [5] presented experimental studies on the frost formation its thermal conductivity and density.

Tao [6] studied the characteristics of frost and how it is formed in two stages namely the liquid phase and the crystal of crystallization phase.

This paper presents the results of an experimental investigation on frost formation over a cold vertical cylinder placed in a wet air stream. Results obtained show the effect of the air flow rate on the distribution of the frost layer thickness around the cylinder, velocity of frost deposition and variation of frost layer thickness with time.

2. EXPERIMENTAL PROCEDURE

2.1. Experimental rig

The experimental rig used in this study is shown in figure 1. Its composed of an open circuit wind tunnel of rectangular test section with acrylic windows at the sides and top for flow visualization and photographing cameras. The cooled tube is fixed vertically in the test section and is fed by the cold secondary fluid being pumped from the secondary fluid cooling talk. This tank is fitted with a cooling coil through which passes the refrigerant from a conventional compression refrigeration system the temperature of the secondary fluid in the talk is controlled and can be adjusted to any required value. The secondary fluid flow rate is measured by a calibrated orifice plate while its temperature at entry and exit to the vertical test tube is measured by calibrated thermocouples.

The rate of air mass flow is controlled by varying the frequency of the driving motor of the tunnel which was calibrated to read volumetric flow rate. The calibration was done by measuring the air velocity by a hot wire anemometer. The tunnel exit section is divided into eight rectangles and the velocity is measured by a hot anemometer placed at the center point of the rectangular section. Of the summation of the product of areas times velocities gives the flow rate at the preset frequency. This procedure is repeated for all the frequency range and the results are plotted in a graph between frequency and the volumetric flow rate.

Humidity of air is provided by cool vaporizer and distributed in the tunnel section by a distributing tube. Dry and wet bulb temperatures are measured before and after the test tube. In order to measure the frost layer growth a digital camera is a high resolution digital camera is used to photograph the cylinder from two different positions: one vertical and the other side wise focalized on the central area of the tube. The photographs are digitalized to obtain the physical positions of the frost layer.

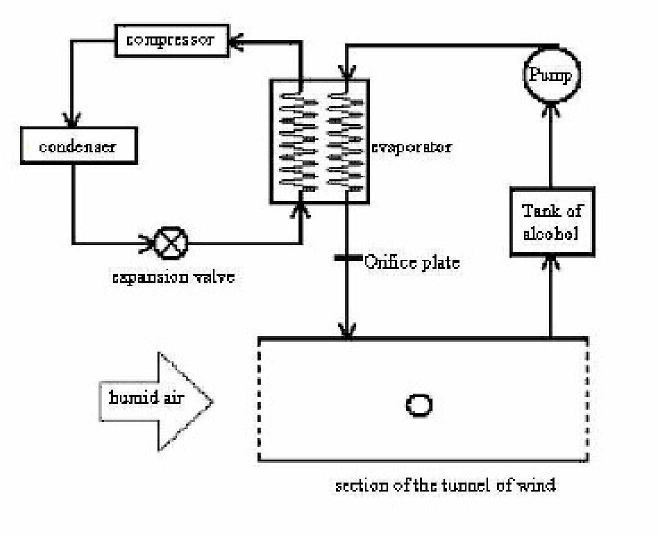

Figure 1. Experimental rig.

The measurements were realized for a range of air flow rate, range of cylinder surface temperature and different flow rate of the secondary fluid. The results are presented in the next section.

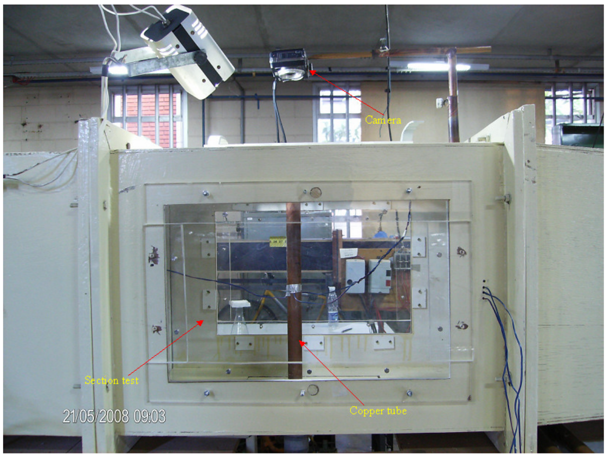

Figure 2. Test section of the wind tunnel.

Figure 3. The tunnel and the experimental system.

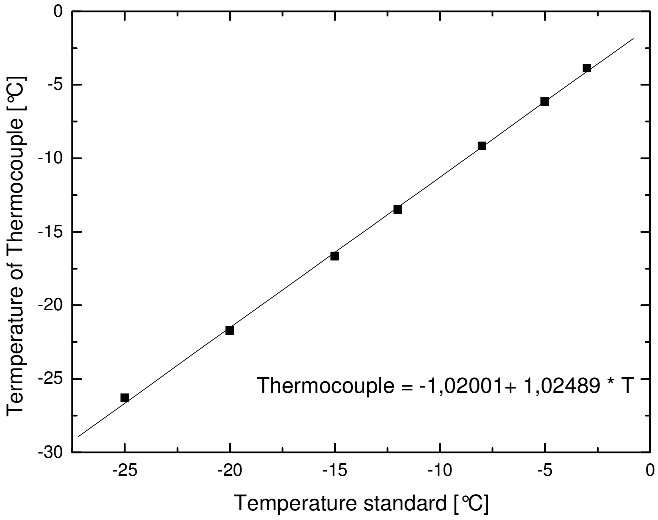

Figure 4 A calibration curve for a thermocouple.

3. RESULTS AND DISCUTTION

The experiments were realized using six values of air flow rates with the air 100% humid. The cold tube surface temperature was fixed at –10°C and the mass flow rate of secondary fluid was adjusted to 45g/s. During the tests photographs were taken of the frost covered cylinder both vertically (along the cylinder axis) and horizontally (normal to its axis). These photographs were then digitalized and the real local frost thickness was obtained.

3.1 Variation of the structure of the frost layer

At the beginning of the process the temperature gradient between the working fluid and the flowing air is high and hence the liquid particle in the humid air collide over the surface and solidified forming ice crystal on the surface of the tube. This process continues and more crystals are formed on the surface in porous like structure. As this layer increases the thermal resistance also increase and the temperature gradients drops in such way that the external surface temperature increases and enhanced by the flowing humid air and starts to change to liquid. When this occurs the thermal resistance decreases and the which leads to increase the temperature gradient and consequently increases the rate of frost deposition. Figures 5 and 6 show both the porous frost formation stage and the glacial frost stage.

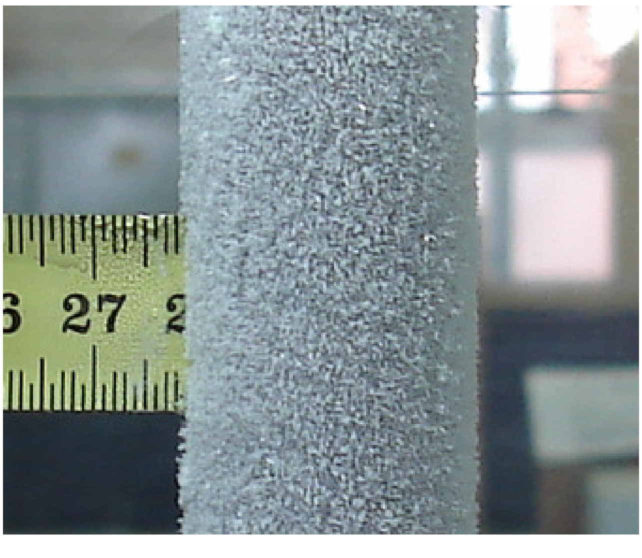

Figure 5. Porous frost formation stage

Figure 6. Glacial frost stage.

3.2 Frost distribution as function of time

Figures 7 to 12 show the frost distribution in the mid section of the cylinder. The results shows the evolution of the frost layer thickness as function of time for the front stagnation point. As can be seen the frost thickness increases with time, initially very frost, nearly linear and then the frost deposition rates starts to slow down and reaching extremely small rate towards the end of the experiment. This behavior which is nearly typical for all experiments can be explained as follows. Initially with very thin layer of frost formed, the effective thermal resistance is dominated by the internal convection and the thermal resistance of the cylinder material. In this case the thermal resistance is the lowest and consequently the heat transfer rate is the maximum possible.

As the frost layer grows thicker its thermal resistance increases, the overall thermal resistance increases maintaining the flow and working conditios the same, the heat flow decreases leading to decreasing the rate of frost formation. Towards the end of the experiment very thick layer is formed, increasing the frost thermal resistance and consequently decreasing substantially the rate of frost deposition.

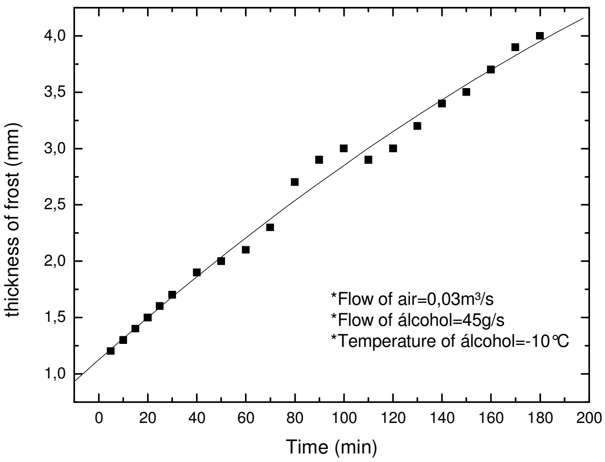

Figure 7. Variation of the thickness of the layer of frost in terms of time for an air flow rate of 0,03m³/s.

If the thickness of frost layer is e (mm) and time t (min), one can obtain the following co-relation for figure 7:

$$e = 1{,}06843 + 0{,}02052.\mathrm{t} - 2{,}56183.10^{-5}.t^2$$

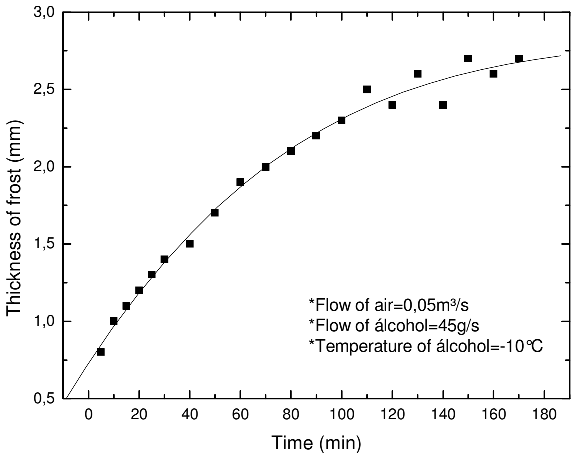

Figure 8. Variation of the thickness of the layer of frost in terms of time for an air flow rate of 0,05m³/s.

For figure 8 the correlation is of the form:

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$$e = 0{,}72797 + 0{,}02488 \cdot \mathrm{t} - 1{,}07481.10^{-4}.t^2 + 1{,}67736.10^{-7}.t^3$$

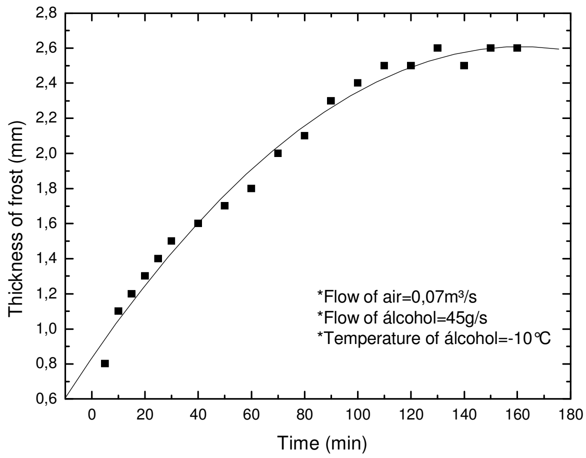

Figure 9. Variation of the thickness of the layer of frost in terms of time for an air flow rate of 0,07m³/s.

For figure 9 the correlation is of the form:

$$e = 0{,}83447 + 0{,}02199 \cdot \mathrm{t} - 6{,}81496.10^{-5}.t^2$$

For figure 10 the correlation is of the form:

$$e = 0{,}86948 + 0{,}02385 \cdot \mathrm{t} - 1{,}20166.10^{-4}.t^2 + 2{,}26042.10^{-7}.t^3$$

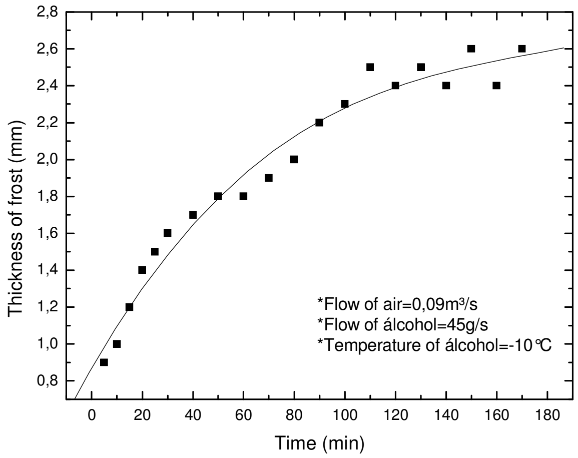

Figure 10. Variation of the thickness of the layer of frost in terms of time for an air flow rate of 0,09m³/s

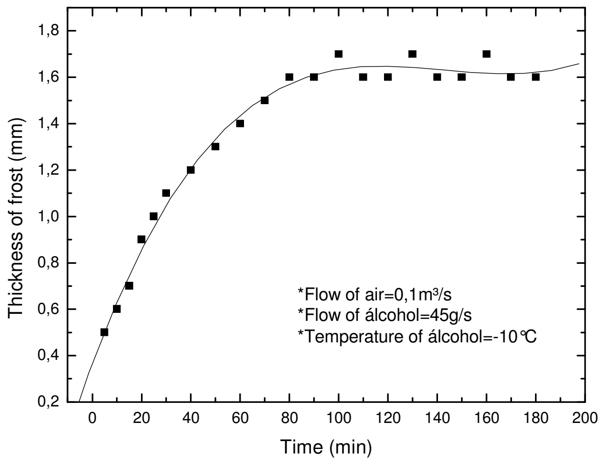

Figure 11. Variation of the thickness of the layer of frost in terms of time for an air flow rate of 0,1m³/s.

For figure 11 the correlation is of the form:

$$e = 0{,}36466 + 0{,}02853 \cdot \mathrm{t} - 2{,}06503.10^{-4}.t^2 + 4{,}82223.10^{-7}.t^3$$

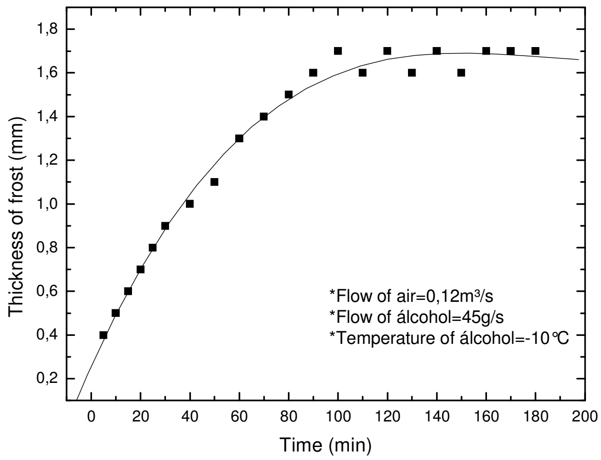

Figure 12. Variation of the thickness of the layer of frost in terms of time for an air flow rate of 0,12m³/s.

For figure 12 the correlation is of the form:

$$e = 0{,}25788 + 0{,}0249 \cdot \mathrm{t} - 1{,}40865.10^{-4}.t^2 + 2{,}57111.10^{-7}.t^3$$

3.3 Angular distribution of frost around the cylinder

Figure 13 shows the angular distribution of frost thickness. As can be seen there some possibly because of vortex shed from the humidity distributor. One can verify that the thickness of the frost stagnation point is maximum.

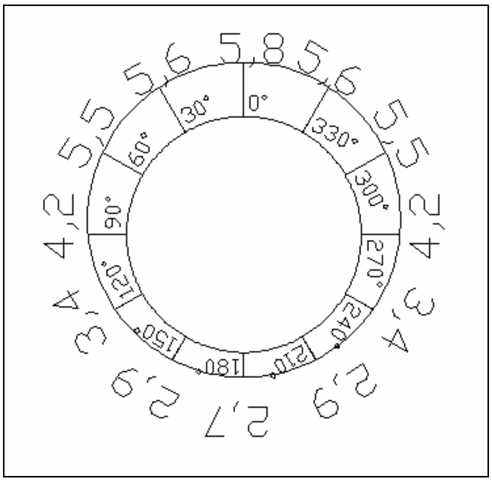

Figure 13. Scanned image representing the variation of the layer of frost around the tube.

3.3 Frost deposition velocity

Figure 14 show the variation of the frost deposition velocity in terms of time. Initially the deposition velocity is extremely high due to the relatively small thermal resistance because of the small layer deposited. As the time passes, the frost thickness increases and consequently the overall resistance increases which leads to slow down the deposition velocity. Finally towards the end of the testing period the overall resistance is extremely high due to the large frost thickness and hence the heat transfer rate is low and consequently the deposition is also low.

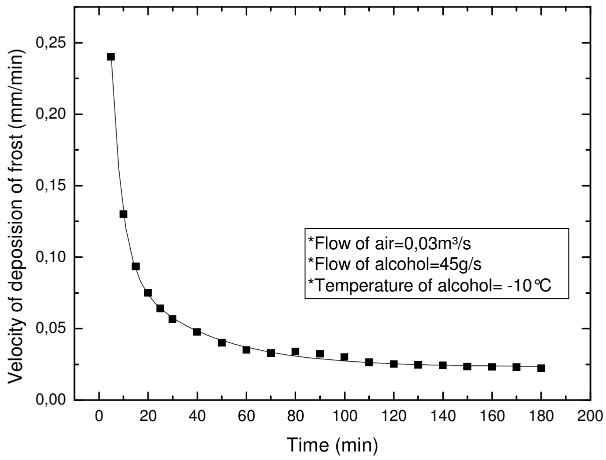

Figure 14. Adjustment made for the change of rate of deposition of frost as a function of time.

If the rate of deposition of frost v (mm / min) and time t (min), one can obtain the following correlation for Figure 14:

$$v = 0{,}02317 + 0{,}45009.\mathrm{e}^{-\mathrm{t}/4{,}40931} + 0{,}08333.\mathrm{e}^{-\mathrm{t}/33{,}4392}$$

3.4 Effect of the humid air flow rate

The influence of the humid air flow rate on the process of frost formation is shown in figure 15. One can observe from figure 15 that as the mass flow of the humid air is increasing the deposited frost thickness tend to decrease this can be attributed to the fact that the increase of the humid air flow rate tends to increase the local friction coefficient and consequently increasing the erasing on the recent solidified particles removing them from the surface and carried away by the flowing air. Then a resulting force is proportional to the square of the $\rho.v^2$ where ρ é a density of the flowing air and v is its mean velocity.

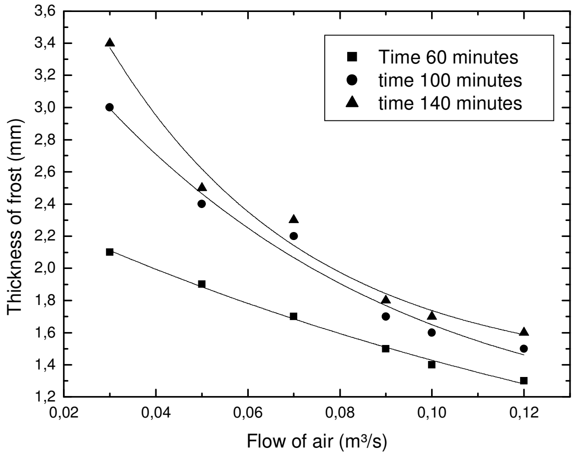

Figure 15. Increase of the frost thickness as function of the humid air mass flow.

Figure 16 shows the variation of the frost deposition velocity with the mass flow rate of the himud air. As can be seen the tendency of the curves confirm the above mentioned arguments. Also one can observe from comparing the three curves that initially the thermal resistance is small and hence high deposition velocity due to the high thermal gradient. As the time goes, the thermal resistance increase because of the increased frost layer resulting in low frost deposition velocities.

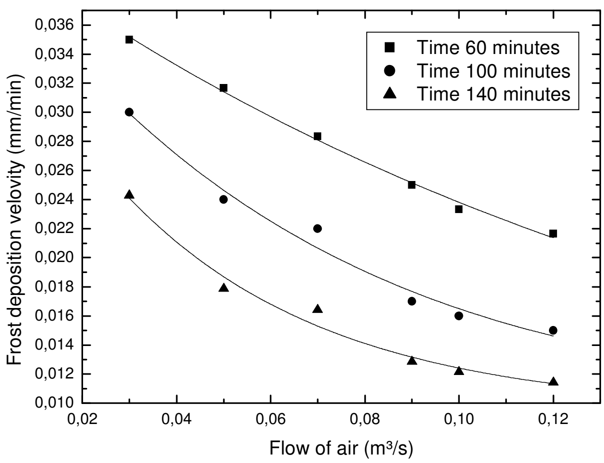

Figure 16. Variation of the frost deposition velocity with the mass flow rate of air.

4. CONCLUSION

From the experimental results one can conclude that thr final thickness of the frost layer as well as the velocity of frost deposition decrease with the increase of the air mass flow rate As can be seen in the results presented, the thickness of the frost as well as the rate of deposition decreases with increasing flow of air. It is important to mention that these results are preliminary results and more work is being carried out on both the experimental and numerical sides including additional geometries of industrial interest.

5. ACKNOWLEDGEMENTS

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