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THE EFFECTS OF HUMIDITY, COMPRESSOR OPERATION TIME AND AMBIENT TEMPERATURE ON FROST FORMATION IN AN INDUSTRIAL FRIDGE*

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Abstract– Fridges are used in various industries, and heat exchanger is one of the main components of these systems; therefore, efficiency analysis of these systems is very important. In many fridges, frost over the heat exchanger tubes or pipes affects the system operation and reduces heat transfer between the refrigerant and ambient, so defrosting systems are usually used to enhance heat transfer. Designing defrosting systems requires sufficient information about frost formation processes. Therefore, the objective of this study is experimental investigation of frost formation over a heat exchanger pipe in a pilot fridge. To do this, some steps are considered. For distinct cases, experiments are done to collect database for frost parameters under desired conditions. Then, based on experimental measurements some correlations are proposed for practical applications of frost growth and defrosting process over heat exchanger tubes.

Keywords– Frost formation, fridge, defrost, compressor operation time, humidity

1. INTRODUCTION

Processes involving heat and mass transfer from humid air to a cold surface, with simultaneous deposition of frost, are of great importance in a variety of industrial equipment. Frost will form on a surface placed in moist air when the temperature of the surface is below the dew point of air and freezing point of water. The frost formation is influenced by many factors. In addition, fridges are commonly used in various industries and usually frost is formed over heat exchanger tubes. Frost over heat exchanger tubes and pipes influences the system operation and reduces heat transfer between the refrigerant and the ambient. Design and operation of any defrosting system requires sufficient information about frost formation process. According to [1], frost density changes greatly with time, and the crystal growth period and layer growth period are distinguished remarkably. They denote that at transition time, density of frost reaches a specified value that depends on the cold surface temperature, which is the end of early-stage period. Many researchers presented numerical and experimental models to predict frosting process over a circular cylinder subjected to humid air cross [2-6]. Review of literature shows that frost studies for forced convection are extensive. Regarding free convection, [7] carried out some experiments about free convection frost growth over vertical cylinders. Tokura et al. [8] reported experimental results of deposited mass and presented dimensionless correlations for frost thickness, conductivity and density. Tanda and Fessa [9] and [10] experimentally investigated the free convection frost growth in vertical channels and offered some correlations for frost properties such as thickness, density and mass. Chen and Oosthuizen [11] carried out some experiments about frost formation on a cooled horizontal cylinder with two cylinders of different diameters, but during most of the experiments, cylinder surface temperature was

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not constant. In addition [12] performed some experiments for frost deposition rate on a horizontal cylinder during free convection. Tahavvor and Yaghoubi [13] developed a numerical model to simulate the early-stage of frost formation in natural convection and a correlation is proposed to predict transition time as a function of all relevant parameters. In addition, they carried out several experiments about frost formation. These experiments were performed on a cold horizontal cylinder under natural convection condition and several correlations were proposed for frost properties as a function of all relevant parameters [14, 15]. In another experimental study, researchers investigated the effect of airflow, humidity, refrigerant temperature and fin types on heat transfer rate [16]. They reported that frost formation rate increased when humidity and airflow increased and refrigerant temperature decreased. Iragorry and Tao [17] determined the frost surface temperature using an infrared thermometer and developed an efficient defrosting system according to their measurements. Liu [18] and [19] experimentally studied the effect of surface paint on frost formation. El Cheikh and Jacobi [20] developed a mathematical model for frost growth and densification on flat surfaces. Frost formation in micro-scale is also studied by some researchers [21, 22]. In addition, [23] experimentally studied the frost formation on a fin-and-tube heat exchanger by natural convection. Yao et al. [24] investigated the effect of flat fins over heat exchanger tubes on frost formation. They have tested the exchangers with one and multi rows of tubes. Guo et al. [25] experimentally studied the effect of air source heat pump system and its performance on frost formation. Recently, according to the experimental measurements, Tahavvor et al. [26] presented the fractal-based model to predict frost layer density and thickness. Nevertheless, from a review of the literature it can be seen that few reports are available about experimental study of frost formation on horizontal cylinders under natural convection in industrial applications such as industrial fridges. Therefore, in this study the aim is experimental investigation of frost formation over heat exchanger pipes in a pilot industrial fridge. To do this, some steps are considered. First, for some distinct cases, experiments are carried out to achieve database for frost parameters under desired conditions. Finally, based on the experimental measurements new correlations are proposed for frost properties in practical applications.

2. EXPERIMENTS

a) Experimental apparatus

In this study, test room is a 5 m × 4 m × 3 m industrial fridge (in Asalooyeh – in the southwest of Iran). Equipment in this fridge allows the user to control ambient temperature and humidity. Test fridge contains both “air-cooling unit” and “humidifier”. These units work until the desired temperature and relative humidity are reached. Capacity of the cooling unit compressor is about 42000 BTU H^{-1} and R22 is used as a refrigerant. Minimum reachable temperature of this fridge is -20°C. Devices used in experimental procedure are listed below:

- Digital thermometer
- Temperature sensors
- Digital psychrometer
- Humidity sensors
- Scaled container

Each device is calibrated to provide excellent sensitivity and stability.

b) Experiments procedure

Before each measurement, all surfaces were cleaned of frost and dried and the following steps were followed:

- Desired temperature and humidity are set and the humidifier and cooling unit are turned on.
- When the fridge reaches the desired temperature and humidity, data acquisition systems are turned on and the programs for collecting the experimental data are loaded and run.
- Defrost system is turned on. Water from the defrost stage is collected into the scaled container to measure the amount of defrosted water.

Several experiments under various conditions (Table 1) are done according to the described procedure. In the experiments, initial temperature range is between 22~24 °C and humidity of the fridge varies between 28~31 % respectively. These initial conditions depend on the atmospheric conditions of Asalooyeh in October and November. Compressor operating time is working time of compressor until it reaches the desired temperature.

In addition, some tests are done to investigate the effect of ambient or initial fridge temperature on frost formation. To achieve this aim, fridge temperature and relative humidity are set to -13°C and 90% respectively. Measurements are done for a range of ambient temperature in four periods of a day. Conditions and results of these experiments are listed in Table 2. Also, in all tests, defrost time is set to 40 minutes to defrost all the frost.

3. RESULTS AND DISCUSSIONS

Experimental measurements for each test are presented in the last two columns of Table 1 and Table 2. One of the important parameters of energy consumption and cost is compressor operation time. Compressor operating time is the working time of compressor until the desired temperature is reached. Experimental measurements contain compressor operation time (*COT*) and volume of defrosted water.

Table 1. Experiments conditions and measurements

Fridge Temp. (°C)	Fridge *RH* (%)	*COT* (min)	Defrosted water (cc)
-7	88	245	335
-7	90	237	340
-7	92	230	345
-7	96	222	375
-9	65	300	220
-9	75	280	310
-9	85	270	360
-9	88	260	360
-9	95	260	380
-11	92	250	365
-11	95	245	460
-11	96	230	470
-13	90	513	375
-13	92	500	405
-13	95	415	475
-13	96	405	585
-15	65	515	270
-15	75	505	290
-15	85	432	340
-15	95	426	480
-17	65	660	365
-17	75	628	380
-17	85	615	405
-17	88	611	430

Table 2. Experiments conditions and measurements

Ambient Temperature (°C)	*COT* (min)	Defrosted water (cc)
6 ~ 8	425	310
13 ~ 15	478	350
15 ~ 17	460	335
17 ~ 19	513	375

Figure 1 shows the *COT* vs. thermostat temperature for different relative humidities. From Fig. 1, it is observed that in constant relative humidity condition, when thermostat temperature decreases, *COT* increases. In addition, it reveals that in constant temperature condition, increasing relative humidity causes reduction in *COT*. According to this figure increasing relative humidity from 65% to 96% decreases the COT around 10%, relative to thermostat temperature. Therefore, relative humidity has no considerable effect on compressor operation time. In *RH* higher than 92% for thermostat temperature of -13°C, *COT* jumps suddenly due to uncontrollable ambient conditions variations.

According to the gathered data, the following correlation is proposed for the relation between thermostat temperature, COT and relative humidity.

$$COT = a + b(RH) + c(RH)^2 + d(T) + e(T)^2 + f(T)^3 + g(T)^4 + h(T)^5 \quad (1)$$

where *T* and *RH* are the thermostat temperature and relative humidity, respectively. Coefficients of Eq. (1) are presented in Table 3. Figure 2 illustrates the correlation between Eq. (1) and the experimental measurements. As can be seen in this figure (and from Table 4) very good agreement exists between experimental data and correlated surface (Eq. (1)).

Figure 3 shows the volume of defrosted water vs. thermostat temperature for different relative humidities. From this figure it is observed that, similar to *COT* in constant relative humidity, when thermostat temperature is reduced, the amount of defrosted water is increased. In addition, it is shown that in constant temperature, increasing relative humidity from 65% to 96% increases the defrosted water around 50~60%. Therefore, opposite to the COT, relative humidity has a considerable effect on the volume of defrosted water. The following correlation proposed a relationship between thermostat temperature, relative humidity and volume of defrosted water (V).

$$V = a + b/(RH) + c(T) + d/(RH)^2 + e(T)^2 + f(T)/(RH) + g/(RH)^3 + h(T)^3 + i(T)^2/(RH) + j(T)/(RH)^2 \quad (2)$$

Coefficients of Eq. (2) are listed in Table 3. Figure 4 illustrates the correlation between Eq. (2) and the experimental measurements. Same as Fig. 2 very good agreement exists between experimental measurements and correlated surface (Eq. (2)).

Figure 5 shows variation of defrosted water vs. thermostat temperature. This figure shows that decreasing the thermostat temperature increased the amount of defrosted water. Figure 6 shows the *COT* vs. relative humidity. From this figure, it is observed that increasing relative humidity decreases *COT*.

The effect of ambient temperature is presented in Fig. 7. This figure shows that when the ambient temperature increases, the amount of defrosted water increases. The relationship between ambient temperature and volume of defrosted water is proposed as follows:

$$V = a + b(Ta) + c(Ta)^2 \quad (3)$$

where *Ta* is the mean ambient temperature.

Equations (1)-(3) are determined from regression techniques based on least–square method. This method recommends various forms for experimental data. Finally, the equation with the best correlation to the original data is selected for each variable. It should be noted that various forms of the equations are due to various types of independent variables.

The R-square values from regression procedure of each correlation are listed in Table 4.

Table 3. Coefficients of correlations

Coefficient	Equation (1)	Equation (2)	Equation (3)
a	-62447.36	7409.08	364.40
b	20.72	-2205125	-12.86
c	-0.14	-751.18	0.75
d	-28608.14	198159861	-
e	-5139.79	-24.68	-
f	-449.70	74718.92	-
g	-19.18	-5648521391	-
h	-0.32	-0.51	-
i	-	645.23	-
j	-	-2257423.65	-

a) Uncertainty analysis

During experiments, errors may be generated from various sources and uncertainty of each quantity should be determined. Table 4 summarizes accuracies for all processes and uncertainties for the correlations (1) to (3).

Table 4. Accuracy of measurements and uncertainties for correlations

Process		Accuracy	
Digital thermometer		1 %	
Temperature sensors		0.2 %	
Digital psychrometer		3 %	
Humidity sensors		1 %	
Ambient temperature		3 %	
Volume of defrosted water		2.5 %	
	Parameter	r-Square	Uncertainty
Equation 1	*COT*	0.96	11.8 %
Equation 2	Volume of defrosted water	0.97	14.2 %
Equation 3	Volume of defrosted water	0.999997	14.2 %

4. CONCLUSION

In this study, frost formation in an industrial fridge is investigated experimentally. Main results of the study are:

- In constant relative humidity condition, as the thermostat temperature reduced, *COT* increased about 9%.
- In constant temperature condition, when the relative humidity increased, *COT* decreased.
- In constant relative humidity, as the thermostat temperature reduces, amount of defrost water increases.
- In constant temperature, increasing relative humidity increases the defrosted water.
- decreasing thermostat temperature increases amount of defrosted water
- Increasing relative humidity decreases *COT*.
- When ambient temperature increases, the amount of defrost water increases

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