Experimental Investigation on Frost Formation in Ammonia Finned Air-Coolers

Rodica Dumitrescu, Anica Ilie, Alina Girip, Madalina Teodora Nichita, Alina Filip

Technical University of Civil Engineering, Bucharest,Bd. Lacul Tei 122-124, Bucharest, 020396, Romania

Rezumat: *Această lucrare prezintă rezultatele experimentale obţinute la testarea unui răcitor de aer cu amoniac, în condiţii de depunere de brumă pe suprafaţa de transfer de căldură. Obiectivul lucrării este acela de a determina influenţa unor factori cheie asupra vitezei de formare şi acumulare a brumei pe suprafaţa rece, în diferite condiţii de funcţionare. S-au studiat: influenţa temperaturii şi conţinutului de umiditate ale aerului la intrarea pe suprafaţa răcitorului, precum şi influenţa temperaturii de vaporizare. De asemena, s-a studiat variaţia densităţii brumei formate în funcţie de temperatura şi conţinutul de umiditate ale aerului la intrarea pe suprafaţa răcitorului. Studiul experimental s-a efectuat pe un stand special proiectat pentru a asigura măsurarea, controlul şi achiziţia de date. Experimentele s-au efectuat în regim staţionar, pentru temperaturi de vaporizare ale amoniacului de -18°C şi -10°C şi puteri de răcire ale aerului cuprinse între 7.6kW si 18.3 kW. Rezultatele experimentale obţinute au fost comparate cu date din literatura de specialitate şi s-a constatat că acestea sunt în concordanţă cu valori obţinute de către alţi cercetători. Scopul acestei lucrări este acela de a furniza o bază de date experimentale, care poate fi utilizată în activitatea de proiectare a răcitoarelor de aer aripate, care funcţionează cu amoniac şi sunt utilizate în aplicaţii din domeniul alimentar, în vederea creşterii performanţei termice a vaporizatoarelor şi a coeficientului de performanţă al instalaţiei frigorifice. Implicit, acest studiu abordează problema permanent actuală a economiei de energie şi a protecţiei mediului înconjurător, prin aceea că utilizează un agent frigorifc natural, şi anume amoniacul (ODP=0 şi GWP = 0), bine cunoscut pentru proprietăţile sale termofizice superioare celor ale agenţilor frigorifici de tip HFC.*

Cuvinte cheie: răcitor de aer aripat, vaporizator cu amoniac, formare şi depunere de brumă, aer umed.

Abstract: *This paper presents results of an experimental investigation conducted on an ammonia air-cooling evaporator working under conditions of frost formation in order to determine the effect of several key factors on the rate of frost formation and growth on finned coil surfaces, under different operating conditions. The influence of inlet air dry bulb temperature and air humidity ratio as well as evaporating temperature has been studied. Frost density, for different dry bulb temperature and humidity air ratio has also been studied. The experimental study was carried out on a specially designed set-up that allowed measuring, control and acquisition of data. Experiments were conducted for ammonia evaporation temperature of-18°C and -10°C and cooling capacity from 7.6 kW to 18.3 kW,* ***during*** *steady state operating conditions. Experimental results have been* *further compared to data in the open literature by authors with similar experimental investigations. The paper concluded that experimental results are in fairly good agreement with other authors work and consequently reliable. The objective of this work is to provide experimental data based on which improved design of ammonia finned evaporator coils used in food freezing or storage as air-coolers may be developed, thus leading to higher thermal performances of evaporators and higher coefficients of performance of the refrigerating system. Implicitly this experimental investigation addresses the permanent objective of energy savings. In addition, by using ammonia as a refrigerant, this experimental investigation addresses also current ecological issues linked to refrigerants. Ammonia is an environment friendly natural refrigerant, known for its zero ozone depleting potential (ODP)l and zero global warming effect (GWP), whose thermo-physical properties are attractive, as compared to HFCs.*

Key words: finned air-cooler, ammonia evaporator, frost formation, moist air.

1. Introduction

When humid air contacts cold surfaces of finned-type heat exchangers used in refrigerators or air-conditioners, frost forms and growths on both surfaces of coils and fins, if the surface temperature is below the freezing temperature of water [1]. So evaporators build up frost continuously when in use [2]. The frost that accumulates on evaporator coils and between the fins interferes drastically with heat transfer and air pressure drop in that it obstructs air passages, diminish the air flow rate over the coil and may eventually block air circulation around the evaporator. It is very important, therefore, that the evaporator surfaces must be defrosted once the limits of economic functioning are exceeded. The lower the fin spacing, the greater care to operating time is required. Once the air flow rate through the coil is reduced, this will further reduce the evaporator temperature, leading to thicker frost formation. The frost in the evaporator coil acts as insulation and diminishes heat-transfer. With decreased heat transfer, the evaporator temperature drops, causing a further decrease in efficiency. If allowed to accumulate further, even liquid flood back to the compressor can occur due to reduced evaporator capacity.

Experimental and numerical studies on heat and mass transfer processes that take place in finned air-cooling evaporators under conditions of frost formation represent major contributions to design analysis of given geometrical configuration in terms of adequate fin spacing, operating coil temperature, defrosting frequency, aiming to achieve maximum efficiency for the evaporator and high refrigerating system COPs [3], [4], [5] .

2. Experimental set-up

The experimental set-up used to investigate the ammonia finned air-cooler is shown in Figure 1 [6]. The air-cooler under study was placed inside the horizontal section of a closed air loop of rectangular shape of 500 x 500 mm in cross section. The insulated galvanized steel made air loop was equipped with multiple regulating and control devices for setting the entering air parameters (dry and wet bulb temperature, humidity ratio, flow rate) and refrigerant parameters, within given ranges, in order to ensure steady state operating conditions.

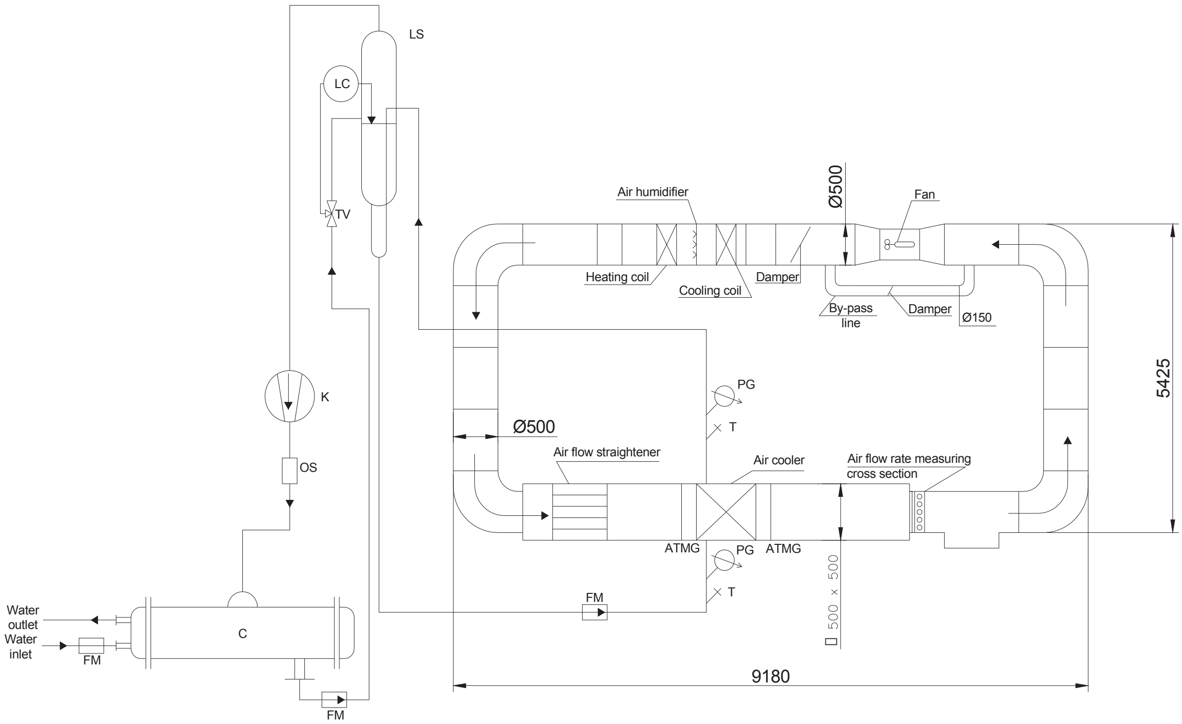

Figure 1. Schematic diagram of the experimental set-up
Legend: LS – liquid separator; OS – oil separator; K- compressor; C – condenser; LC – level control; TV – thermostatic valve; ATMG – air temperature measuring grid; FM – ammonia flow meter; T – temperature sensor; PG pressure gauge.

The transparent top cover of the air loop enables visualization of frost formation and growth on the fins and coils of the ammonia finned evaporator coil (Photo 1).

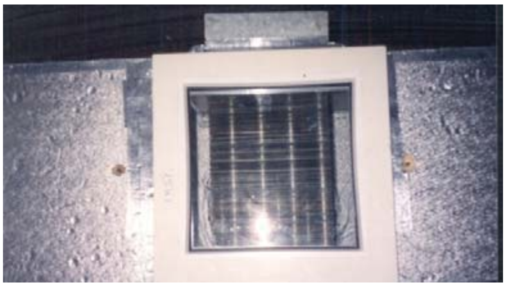

Photo 1. Finned air-cooler inside the air loop – plan view

Geometrical configuration of the ammonia finned air-cooler is shown in Figure 2. As it may be observed, the air-cooler under study uses a staggered tube bundle system of 4 parallel coils, of 8 horizontal tubes each. Coils are made from steel tubing and fins are made of aluminum. The outer diameter of the tubes is 25 mm and the tube spacing is 70 mm on equilateral centers. Corrugated fins of 0.4 mm thickness are spaced 5.25 mm apart.

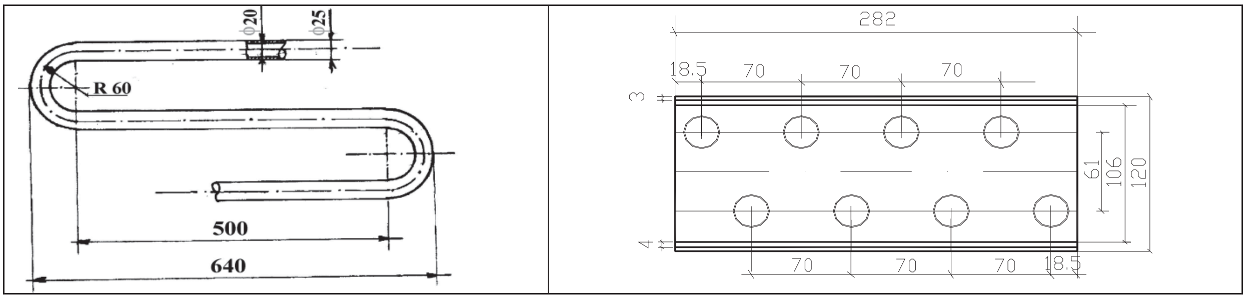

Figure 2. Geometrical configuration of coils and fins

Photo 2 shows the insulated single stage mechanical vapor compression refrigeration system used for the experimental investigation. The ammonia air-cooling evaporator is fed by gravity circulation from the vertical liquid separator. Humid air of controlled inlet parameters is simultaneously directed over the finned coil, flowing through the unit.

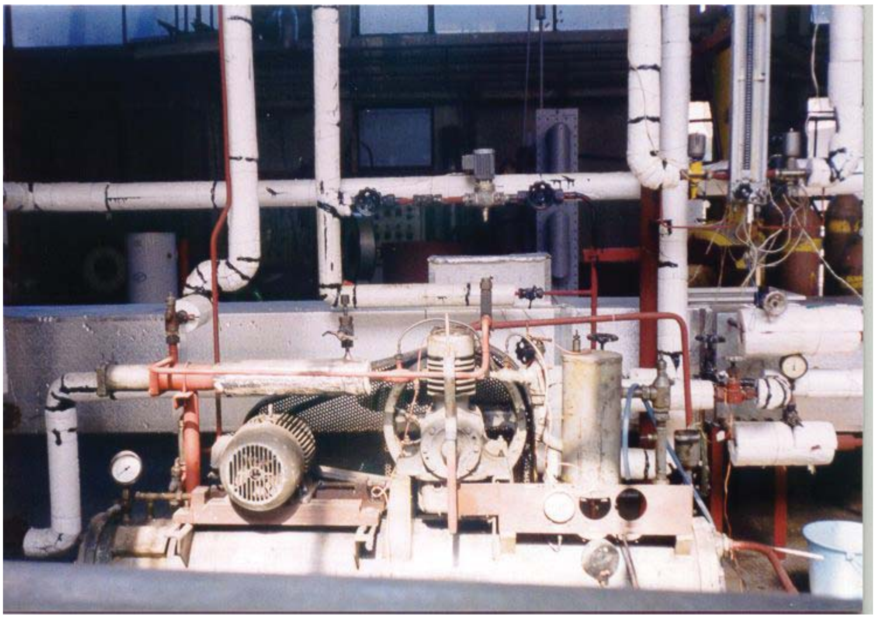
Photo 2. Refrigeration system – overall view

3. Methodology

Experimental investigation has been carried out on the ammonia finned air-cooler described above during steady state operating conditions. It was considered as such the regime characterized by maximum ±5% variation of the measured parameters, along 10 consecutive readings, at 10 minutes apart. The goal of the experiments was to determine the effect of several key factors on the rate of frost formation and growth on the finned coil surface under study, under different operating conditions [6], [7], [8]. The influence of inlet air dry bulb temperature and air humidity ratio as well as evaporating temperature has been studied. Frost density, for different dry bulb temperature and humidity air ratio, has also been studied.
Experiments were conducted under the following operating conditions:

- cooling capacity from 7.6 kW to 18.3 kW;

- dry bulb temperature of inlet air ranging from +10 °C to +20°C;
- humidity ratio of inlet air ranging from 5 g/kg to 9 g/kg;
- air velocity in the front section of the air cooler with dry surface: 3,3 m/s;
- ammonia evaporating temperature of-18°C and -10°C;
- maximum operation time: (70 …135) min.

As presented in detail in [6], cooling capacity of the ammonia finned air-cooler with frost formation has been experimentally determined in two different ways, namely: based on the energy balance of the refrigeration system and based on the cooling capacity on the air side, [6]. Only experimental $\dot{Q}_0$ values that satisfied the energy balance within a deviation of ± 7% have been considered reliable and considered in further calculations. Once the system reached steady state conditions, both frost mass and height have been measured, after certain periods of time, considered as significant. Experiments have been considered completed as frost thickness reached maximum acceptable values, in terms of economic operating costs, namely 2.2 to 2.3mm on each fin side, given an overall fin spacing of 5.25 mm. It has thus been determined the maximum operating time of refrigeration cycle before defrosting is needed.

Mean density of the frost, ρ_f^m, has been calculated, by:

$$\rho_f^m = \frac{M_f}{A \cdot \delta_f^m}, \text{ [kg/m}^3\text{]} \qquad (1)$$

where: - M_f -measured mass of frost accumulated on coils and fins, [kg]; δ_f^m - mean frost height, [m]; A – overall heat transfer area of the finned air-cooler.

Primary measurements in the experiments were:

- on air side: dry bulb temperature (t_1^{dry}, t_2^{dry},), wet bulb temperature (t_1^{wet}, t_2^{wet}), both at the inlet and outlet of the finned air-cooler, volumetric flow rate (Figure 1);
- on ammonia side: inlet and outlet temperature and pressure, liquid volumetric flow rate (Figure 1);
- on water side: temperature inlet and outlet of the condenser and volumetric flow rate (Figure 1);
- mass of the frost.

Temperatures were measured using type K thermocouples with reading accuracy within ± 0.1°C. Air volumetric flow rate was measured with a hot wire anemometer placed into air stream that provided a direct reading of air velocity with an accuracy of 2 to 5% of reading over the entire velocity range. Water volumetric flow rate was measured with a Danfoss electronic flow meter that had a reading accuracy of ±3% and liquid ammonia volumetric flow rates were measured by Coriolis type flow meter that had a reading accuracy of ±3%. Mass of the frost was measured using a precision balance with an accuracy of 3% of reading over the entire measuring range. All sensors were calibrated prior to testing.

4. Experimental results

4.1. Effect of air temperature on the rate of frost growth

Figure 3 shows the variation of frost thickness in time, for different air temperatures and humidity ratios at the air-cooler inlet. Experiments have been performed for the same evaporating temperature of -10°C, humidity ratio of inlet air of 5g/kg, 7g/kgand 9g/kgand three different air dry bulb temperatures of +20°C, +15°C and +10°C. It may be observed from Figure 3 that the effect of entering air temperature on the rate of frost growth is very low, since regardless of temperature, frost thickness of (2,2 … 2,3) mm is formed after approximately 135 minutes, given the air humidity ratio of ≅ 5 g/kg.

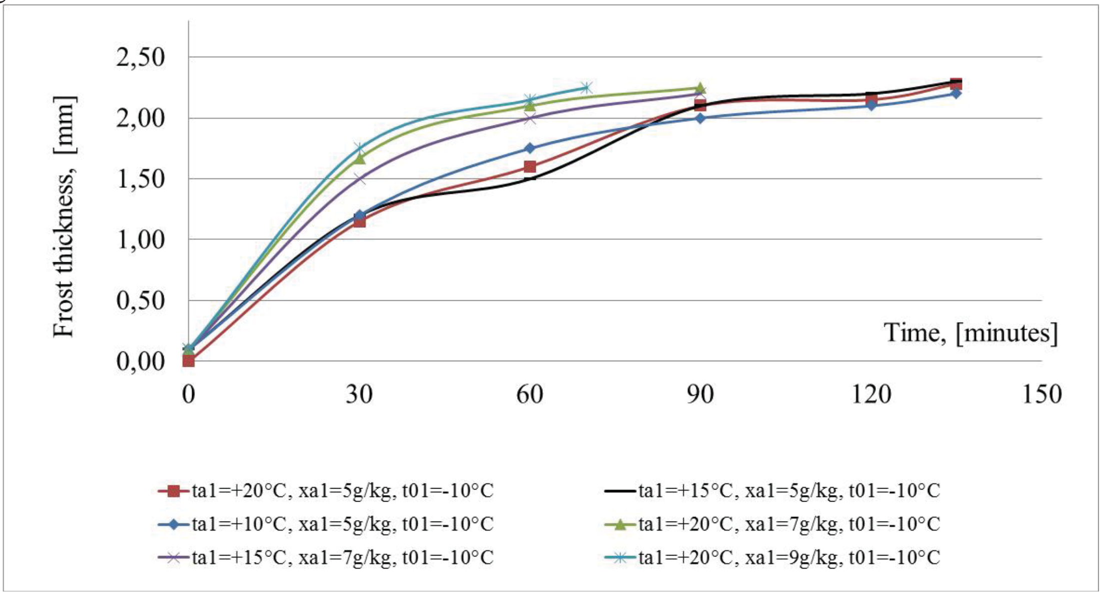

Figure 3. Effect of air temperature on the rate of frost growth

The same conclusion can be drawn from Figure 3, with respect to the air humidity ratio of ≅ 7 g/kg; however, in this case the economicoperating time needed to form the same frost thickness of (2,2 … 2,3) mm decreases to approximately 90 minutes.

4.2. Effect of air humidity ratio on the rate of frost growth

As already mentioned above, it is also obvious from Figure 3 the strong effect of different entering air humidity ratio on frost thickness variation in time.

This normal trend of economicoperating time decrease with an increase in entering air humidity ratio is comparatively depicted in Figure 3. Considering the same air temperature of +20°C, the rate of frost accumulation to build the same (2,25 … 2,275) mm of fost thichness decreases by 33% with an increase in air humidity ratio from 5g/kg to 7g/kg, and by 48% with an increase in air humidity ratio from 5g/kg to 9g/kg.

Considering the same air temperature of +15°C, the rate of frost accumulation to build the same (2,25 … 2,275) mm of fost thichness decreases by 33% withan increase in air humidity ratio from 5g/kg to 7g/kg.

The experimental results shown in Figure 3 are fully consistent with those obtained by Mao et al. (1992) [7], Lee et al. (1997) [8], Ismail (1999) [9].

4.3. Effect of evaporating temperature on the rate of frost growth

Frost thickness is plotted against time for two different evaporating temperatures of -10°C and -18°C in Figure 4. Experiments have been conducted for entering air dry bulb temperature of +20°C, +15°C and +10°C and entering air humidity ratio of 5g/kg. It may be noted from Figure 4 that the rate of frost growth increases on average by 41%with a decrease in evaporating temperature from-10°C to -18°C, so that the same maximum frost thickness within the range of (2.3 ... 2.33) mm, is formed in approximately 80 minutes, given the air humidity ratio of 5g/kg, regardless the air dry bulb temperature at the ammonia finnedair-cooler inlet.

These results are consistent with those indicated by Tao et al. (1993a) [10].

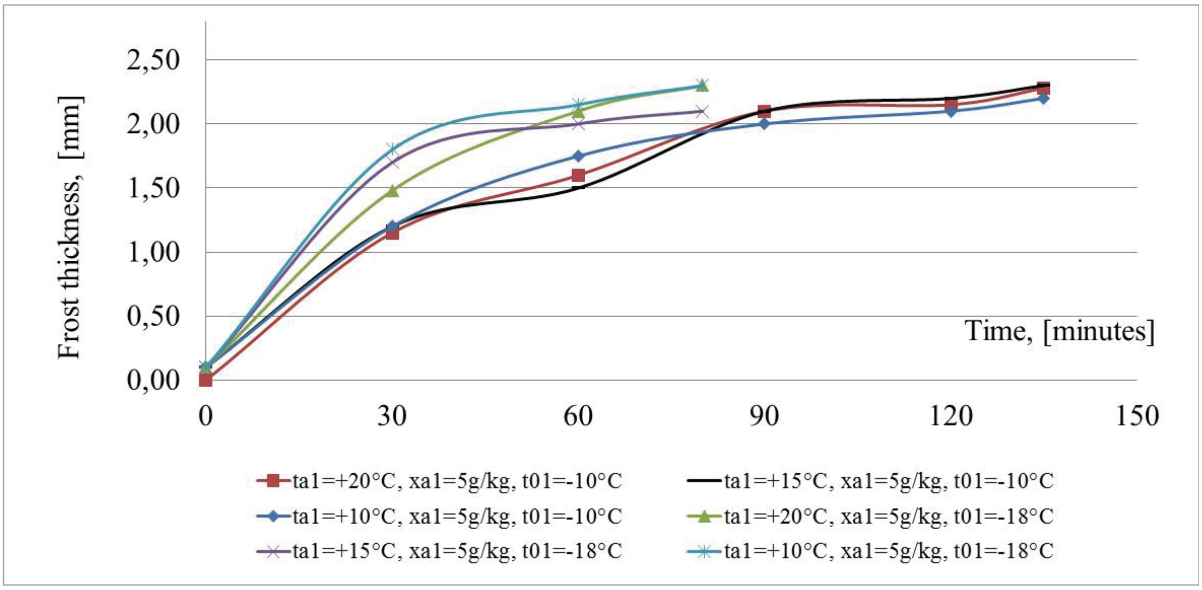

Figure 4.Effect of evaporating temperature on the rate of frost growth

4.4. Effect of air temperature and humidity ratio on average frost density

Figure 5 shows average frost density against time for air temperatures of +20°C, +15°C and +10°C, air humidity ratios of 5g/kg and 7g/kg and the same evaporating temperature of -10°C. It my be observed from Figure 5 that the average density of the frostincreasesto(100 ... 125) kg/m^3, after 135 minutes, given the air humidity ratioof 5g/kg and the evaporating temperature of -10°C.These resultsare consistent with those obtained by Tao et al. (1993a), which indicate an average frost density of approximately 110 kg/m^3,after 120 minutes operating time, for-10°Ctemperature of the evaporator surface, +20°C air temperature and 8.854 g/kg air humidity ratio.

For higher values of air humidity ratio (7g/kg) and the same evaporating temperature of -10°C, the average maximum density of the frost reaches approximately 135kg/m^3, showing almost no influence from the air temperature. Density falls roughly in the same range of values as the previous ones, but corresponds to a lower economic operating time of 90 minutes, as compared to the 135 minutes discussed above.

Since the key factor in frost formation and growth is the air humidity ratio, it may be seen from Figure 5 that different values of air temperature do not significantly influence the slope of the average frost density.

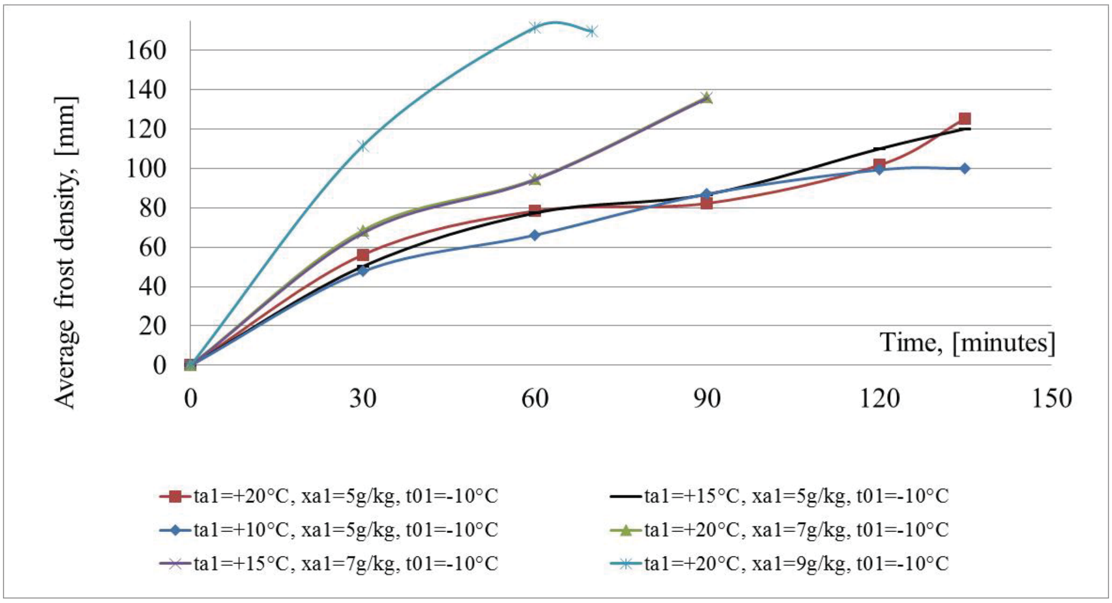

Figure 5. Effect of air temperature and humidity ratio on average frost density

5. Conclusions

In the present work the effect of several key factors on the rate of frost formation and growth on the finned coil surface of given geometrical configuration, under different operating conditions, has been investigated experimentally. Frost density, for different dry bulb temperature and humidity air ratio, has also been studied and experimental results have been further compared to data in the open literature by authors with similar experimental investigations. Experimental results led to the following conclusions:

- the effect of entering air temperature on the rate of frost growth is very low, since regardless of temperature, frost thickness of (2,2 … 2,3) mm is formed after approximately the same economicoperating time, for fixed air humidity ratio and evaporating temperature;
- the key factor in frost formation and growth is the air humidity ratio; it causes the strongest effect on frost thickness growth in time,for fixed evaporating temperature; as a consequence, the economic operating time strongly decreases with an increase in in air humidity ratio;these experimental results are fully consistent with those obtained by Mao et al. (1992), Lee et al. (1997), Ismail (1999);
- the rate of frost growth strongly increaseswith a decrease in evaporating temperature, for a fixed air humidity ratio, regardless the air dry bulb temperature at the ammonia finned air-cooler inlet;these results are consistent with those indicated by Tao et al. (1993a);

- the average density of the frostranges from100kg/m^{3}to135kg/m^3, depending on the air humidity ratio, for a fixed evaporating temperature.These resultsare consistent with those obtained by Tao et al. (1993a).

6. References

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