ON THE INFLUENCE OF FROST ON THE PERFORMANCE OF UNIT COOLERS

1. INTRODUCTION

Dry operating conditions are quite uncommon in real applications of unit coolers, since some humidity is generally present in cold rooms. The effective merit of an unit cooler should therefore be evaluated by considering its performance under operating conditions close to reality, that is to say by accounting for the effects of the changes of phase (from gaseous to liquid, or, for wall temperatures below 0°C, to solid) of the water fraction present in the humid air. It is well known that frost formation on heat exchange surfaces significantly penalizes the unit coolers performance. The extent and the rate of such a performance degradation depend upon a very large number of factors, including the cold room operating conditions (air temperature, relative humidity), the cooler characteristics (coil geometry, heat transfer surface, fin spacing, etc.), fan characteristics, the refrigerant compressor, etc.

Due to this large variety of conditions inflencing the performance, it would be very difficult to univocally define - and even more difficult to measure - the "average" capacity of an unit cooler under frosting conditions. To avoid uncertainties and undue complications in acceptance tests, all international standards identify unit cooler capacity by referring only to "dry" operating conditions: in this way, steady-state conditions can be obtained and the unit cooler capacity can be measured with the desired accuracy. It is then left to manufacturers the task of indicating to the customers how to extrapolate the behavior of their equipment from dry, steady state conditions to real operation with humid air.

Lu-Ve Contardo and Politecnico di Milano, respectively the largest manufacturer of unit coolers and the most important engineering university in Italy, have been involved since almost a decade in a common research program aiming to investigate, theoretically as well as experimentally, the influence of frost on the performance of unit coolers. It is purpose of this paper to briefly summarize some of this activity.

2. PHYSICAL BACKGROUND

The physical mechanism of frost formation is a highly complex one, deeply investigated in the scientific literature. An example of the results of detailed tests carried by flowing cold humid air on a flat surface is represented in fig.1. Given this complex pattern, it is not surprising that the scientific community has not yet reached a generally accepted consensus on theoretical methods for simulating the frost influence on the heat exchangers performance. In fact, consensus is far to be reached even on correlations proposed to predict the basic thermodynamic and transport properties of frost, that are the first, indispensable step required to develop any calculation procedure on frost effect on coolers performance: as shown in fig.2 and 3, the scatter on published correlations concerning frost density and thermal conductivity is dramatically high.

From a physical point of view, the major effects of frost formation on the heat exchanger performance are twofold:

1. the frost layer of the heat transfer surface acts as an insulation, thereby increasing the thermal resistance between air and refrigerant; to simulate this effect, assumptions are required on frost thickness and thermal conductivity;

2. the presence of frost increases the pressure drop of the air flowing through the heat exchanger, thereby decreasing the air flow rate; a lower air velocity not only decreases the air-to-wall heat transfer coefficient, but penalizes also the temperature differences between air and refrigerant, that are the driving force of heat exchange.

The relative importance of these two effects, for a well designed heat unit cooler (with a proper matching between coil and fan characteristics) is generally comparable, as shown in fig.4, where the capacity variation of a unit cooler as a function of the mean frost layer thickness is depicted. Three lines are represented: the line a) accounts only for the thermal insulation effects and is computed by assuming that the air flow is not affected by the increased drag related to frost formation; the line b) accounts only for the influence of the air velocity variation and is computed by assuming very high values of frost thermal conductivity; eventually, the line c) accounts for both effects.

Other effects related to frost formation should however be accounted for in developing a reliable theoretical simulation:

- due to change of phase, the air-to-wall heat transfer coefficient is enhanced with respect of dry conditions: in fact, at the beginning of the frosting process, the capacity of the unit cooler is favorably affected by this heat transfer enhancement, as can be seen by comparing the "dry" capacity indicated in fig.4 with values under frosting conditions; the ratio between wet/dry capacities is primarily a function of air temperature and humidity, as shown in the example of fig.5, and is remarkably larger than unity at relatively high temperatures;
- the frost deposition on heat transfer surfaces is not uniform, since it is strongly affected by

wall temperature variations (for instance, a thicker layer is always found in the proximity of tube surfaces, which are at a lower temperature than fin surfaces; the presence of refrigerant super-heating can prevent frost formation in the first rows of the evaporator, etc.) and by air thermodynamic conditions (air varies both absolute humidity and temperature form inlet to outlet) and velocity (air velocity distribution can be not uniform throughout the coil);

- frost formation alters the heat exchanger geometry, mainly by changing the surface roughness, which affects heat transfer as well as friction coefficient
- due to frost induced variation of cooler capacity, the refrigerant flow rate inside the tubes changes, thereby inducing variations of heat transfer coefficient inside the tubes.

3.RESEARCH AND DEVELOPMENT ACTIVITY GOING ON AT LU-VE CONTARDO

The simulation procedure developed by Lu-Ve for predicting unit cooler performance under frosting conditions can be described, for sake of simplicity, by identifying the following main steps:

<u>"dry and clean "performance</u>

- correlations for predicting air-side heat transfer and friction coefficient in dry conditions: although several theories have been developed, sufficiently accurate relations can be obtained only by experimental tests, especially when advanced, turbolated heat transfer surfaces are adopted. Tests are performed in an air tunnel (fig.6), by measuring the overall heat transfer coefficient and calculating the air-side heat transfer coefficient (including fin efficiency effects) by well established correlations of the internal heat transfer (water inside the tubes);
- correlations for predicting internal heat transfer coefficient: also in this field, literature indications are not sufficiently reliable to cover all situations which can occur in a modern advanced unit cooler. The test rig developed by Lu-Ve Contardo (fig.7) allows direct measurement of internal heat transfer and friction coefficients at various mass flows. Tests can be carried out for tubes having internal turbolators of various geometry. Fluids inside the test tube can also be varied, including new refrigerants, zeotropic mixtures, highly viscous single-phase glycoles, etc.;
- fan characteristic: the relationship between air flow and pressure head of fans is experimentally derived in a wind tunnel; direct measurement of the flow rate in the unit cooler in dry conditions is then performed, to account also for the influence of cooler frame on air flow;
- once reliable correlations for internal and external heat transfer coefficients are derived

and precise air-flow rate is measured, simple theoretical calculations provide the designer with highly accurate predictions of the "dry" performance of an unit cooler; these predictions are generally confirmed (within 1-2%) by direct measurement of the unit cooler performance carried out in thermostatic cold rooms, either at Lu-Ve or in other independent laboratories.

frost influence

- a computer program was developed to simulate frost effects, based on simple hypotheses, which require calibration by experimental tests:

- the unsteady behavior of the cooler is calculated by a sequence of steady-state conditions at specified time intervals;
- the time evolution of "external" conditions can be defined by the user, by adopting various alternate assumptions: either by specifying constant air inlet properties (humidity and temperature) and constant evaporating temperature, or by simulating the thermal balance and the water mass balance of the cold room, the refrigerant cycle (compressor, condenser, expansion valve) and the regulating philosophy;

- the steady-state calculation of the unit cooler under frosted conditions is carried out by "conventional" approach, based upon the following hypothesis:

air flow calculation

- the air flow rate is computed by matching the fan characteristic line with the pressure drop resulting from friction coefficients of frosted coil;
- the pressure drop of "dry and clean" coil is modified by considering the increased blockage of frost as well as the increase of friction coefficient;
- the frost blockage is computed from the previous time step calculation, by dividing the frost mass deposit by the frost density and distributing the resulting volume on fin and tube surfaces; this operation requires: (i) an empirical correlation providing frost density as a function of operating variables; (ii) an empirical rule to divide the frost formation between fins and pipes surface;
- the increase of friction coefficient must be evaluated by empirical correlations;

heat transfer calculation

- the air-to-fin heat transfer coefficient is computed by modifying the dry-condition value to account of: (i) the modified air velocity (velocity variation is due to modified air flow as well as to modified fin blockage: the two effects are counteracting); (ii) the effect on heat transfer of change of phase of air humidity: a modified version of the so-called "potential enthalpy theory" is used; (iii) the alteration of surface roughness caused by frost;

- the thermal insulation due to the frost layer is accounted for by introducing an empirical correlation providing frost thermal conductivity as a function of operating variables and by assuming an uniform thickness for the frost deposit;
- the so-called "fin efficiency" , which accounts for temperature gradients along the fins, is modified (slightly increased) to account for the increased thermal conductivity along the fin caused by the frost deposit;
- the internal (refrigerant-side) heat transfer coefficient is computed according to actual flow rate.

The above outlined calculation procedure incorporates the influence of all basic phenomena related to the frost formation influencing the cooler performance, but requires an extensive "calibration" of the several arbitrary coefficients/correlations introduced. In particular: (i) the frost properties (density and thermal conductivity), (ii) the variation of air-to-wall heat transfer and friction coefficients in presence of frost, (iii) the frost repartition between fin and tube surfaces and (iv) the effects on overall pressure drop caused by non-uniformity of frost deposit.

An extensive experimental activity was therefore carried out at Lu-Ve Contardo laboratories to gather all necessary information. Tests were carried out on a large number of evaporators, characterized by a variety of design features, ranging from advanced models with internally microgrooved tubes and turbolated fins to more conventional units having plain tubes and flat fins, and for a variety of fin spacing, rows number, fan models, etc. The whole range of application of commercial and industrial unit coolers was investigated, namely air temperatures from +5 °C to -25 °C and relative humidity up to 90%.

The adopted test procedure can be summarized as follows:

- the unit cooler (either one or two, since some tests are carried out for comparing different models under identical operating conditions) is placed in the thermostatic cold room (fig. 8);
- performance is firstly measured in dry, steady-state conditions; the accuracy of the measurement is checked by comparing the thermal power introduced in the cold room to the one obtained by enthalpy difference and mass flow measurement on the refrigerant side; a further check is made by comparing the experimental value to the one resulting from theoretical calculation;
- steam is then introduced in the cold room, which is kept at constant temperature and humidity by proper control procedures;
- the refrigerant evaporating temperature is also kept constant, by acting on the refrigerant compressor;

- the refrigerant superheat is kept constant by a precision expansion valve;
- the evolution of all significant parameters is recorded; in particular, the air flow variation is computed by measuring the pressure drop across the coil and the variation of the electric power consumption of the fan electric motor, while the the cooler capacity variation is computed by measuring the refrigerant mass flow and inlet/outlet thermodynamic conditions;
- at the end of the test, defrosting is performed and the mass of collected water is measured.

It was found that the most critical parameter in the calculation procedure is the correlation of frost density, that directly affects the pressure drop variation and consequently the air mass flow and indirectly acts (via the thermal conductivity correlation) on the thermal resistance of the frost layer. Once proper correlations are introduced for frost properties and the other quoted parameters are calibrated, the agreement between experiments and tests is satisfactory. Calibrations proved to be substantially not depending on operating conditions (air temperature, humidity), or coil and fan characteristics.

The results shown in figures 9-11, where comparisons between experimental and theoretical evolution of cooler capacity are depicted, confirm this statement.

4. CONCLUSIONS

The frost formation mechanism and its influence on the capacity of unit cooler is a highly complex process, that cannot be treated by rigorous theoretical approach. This paper describes the semi-empirical approach developed by Lu-Ve Contardo and Politecnico di Milano, which embodies theoretical methods accounting for the most important physical phenomena related to frost and affecting cooler performance. This calculation method required an extensive calibration procedure based upon a large series of tests carried out at Lu-Ve laboratories. Some results are shown that confirm the accuracy of the described method, that is currently used by Lu-Ve Contardo for the design of commercial and industrial unit coolers and proves to be particularly useful for selecting the right matching between fan and coil characteristics.

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CAPTIONS OF FIGURES

Fig.1Frost formation process. Results obtained by Japanese researchers (Ref. 1 and 2) on a flat surface with air velocity of 4 m/s (fig.1a) and 1.6 m/s (fig.1b) (Ref. 1 and 2)

Fig.2Frost density - Comparison of correlations proposed in the technical literature (Ref. 3-5)

Fig.3Frost thermal conductivity - Comparison of correlations proposed in the technical literature (Ref. 6-9)

Fig.4Relative variation of the unit cooler capacity as a function of the mean frost thickness (dotted line refer to "dry and clean" situation).
curve a): constant air flow rate
curve b): effect of air flow variation (frost thermal conductivity assumed equal to infinity)
curve c): cumulative effect of air flow variation and thermal insulation of the frost deposit

Fig.5Theoretical wet/dry capacity ratio at the beginning of the frosting operation as function of air inlet temperature and relative humidity

Fig.6The air tunnel for air-to-fin heat exchange measurements at Lu-Ve Contardo thermodynamic laboratory; the tunnel can operate with dry and wet air (Ref.10)
a) photograph
b) operating scheme

Fig.7The test rig for at internal heat transfer coefficient measurements at Lu-Ve Contardo thermodynamic laboratory; the rig can measure heat transfer coefficients and friction factors in evaporation, condensation, single-phase processes, with simple fluids or zeotropic mixtures (ref.5):
a) photograph
b) operating scheme.

Fig.8a)The thermostatic cold room at Lu-Ve Contardo thermodynamic laboratory; tests can be carried out in dry and wet conditions;
b)enlarged photograph of an unit cooler with clean (upper part) and frosted (lower part) surfaces at the end of a test.

Fig.9Time evolution of cooler capacity under frosting conditions: comparison between theory and tests.

Fig.10Time evolution of cooler capacity under frosting conditions: comparison between theory and tests.

Fig.11Time evolution of cooler capacity under frosting conditions: comparison between theory and tests.