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IN-SITU EVAPORATOR HEAT TRANSFER EXPERIMENTS FOR DOMESTIC REFRIGERATORS

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ABSTRACT

This paper describes a specially prepared experimental set-up to measure the heat transfer characteristics of evaporators placed inside a domestic refrigerator or freezer. The evaporators can either be of the forced air or natural convection type (optionally integrated into the cabinet wall). The paper discusses the special arrangements needed in this experimental set-up to accurately determine the very low heat flows occurring (from 20 to 80 W). Special attention will be paid to the refrigerant flow control needed to set a certain superheat at the evaporator outlet. It will be shown that the same apparatus can also be used to measure the heat transmission through the cabinet walls. Trial experiments, in which the radiation coefficients of the cabinet walls were varied, influencing the heat transmission coefficients, give an example of the capabilities of the system.

INTRODUCTION

This paper describes a test bench for measuring the performance of evaporators used in domestic refrigerators or freezers. This "Evaporator Calorimeter" is able to determine the overall heat transfer coefficient of evaporators in practical circumstances. This means that the evaporators are measured the way they are integrated into the refrigerating appliance using the original refrigerant (HFCs, HCFCs, hydrocarbons and mixtures are all possible). The set-up controls the inlet and exit conditions of the refrigerant in the evaporator. Next to the evaporator heat transfer the overall heat resistance of the walls of the appliance is also derived. In the section below the measurement principle will be explained followed by a detailed description of the measurement set-up. The special control algorithms applied in the measurement set-up are being discussed and, finally, an example experiment performed with the set-up will be presented.

MEASUREMENT PRINCIPLE
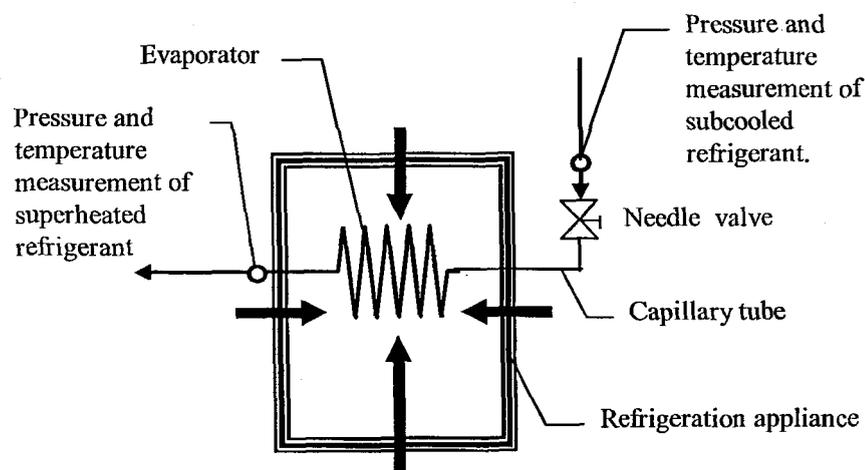
Fig. 1: measurement principle

Fig. 1 explains the measurement principle. Sub-cooled refrigerant is supplied to the evaporator via a throttling device. The enthalpy of the refrigerant before expansion can be determined by measuring the pressure and temperature. The enthalpy at the entrance of the evaporator is then assumed to be equal to the enthalpy before expansion (adiabatic expansion). After the evaporation process, the evaporator exit enthalpy is determined by measuring the superheat and the pressure. By multiplying the enthalpy difference between the evaporator inlet and exit with the refrigerant massflow, the evaporator heat transfer can be determined.

In a stable condition with constant temperatures in and outside the appliance, the heat absorbed by the evaporator equals the heat transfer through the walls of the appliance. Knowing the heat transfer and the temperatures of the evaporator, appliance and ambient, overall heat transfer coefficients for the evaporator as well as for the appliance can be determined simultaneously.

In this experimental set-up special arrangements are needed to accurately determine the very low heat flows occurring (from 20 to 80 W). For these heat flows it can be calculated that refrigerant flows as low as 0.1 g/s are possible. To set the superheat at the evaporator exit special arrangements had to be made to control the flow. A conventional thermostatic expansion device cannot be used here because the capacities needed are too low and because it is impossible to set the small superheat values sometimes required.

THE MEASUREMENT SET-UP

The measurement set-up is schematically shown in Fig. 2. The set-up can, in fact, be considered as a complete refrigeration system excluding the evaporator. To evaporate the refrigerant the evaporator of the appliance being tested is used.

A bypass tube from the discharge to the suction side of the compressor is included in the circuit. In this bypass tube a metering valve is placed, which is used to modify the bypass-flow. By changing the bypass-flow the flow of refrigerant through the principle circuit can be varied. The metering valve is a hand adjustable valve and serves to roughly set a certain refrigerant flow in the circuit. To fine-tune the refrigerant flow through the circuit during a measurement cycle a compressor with variable capacity was needed. The compressor used is a 24 V D.C. type, which can be regulated in the range of 18 to 30 V, resulting in different operating frequencies and therefore different mass flows. To regulate the compressor speed a software PID controller is used.

After the compressor the refrigerant flows into the condenser. For a stable measurement it is necessary to keep the condensation temperature at a constant value. For this objective an oversized coaxial heat exchanger (between the refrigerant and water) is being used. The water flow is also strongly overdimensioned and therefore the refrigerant will condense at a temperature very close to the water temperature. With this construction it is possible to indirectly control the condensation temperature (pressure) by controlling the water temperature. To control the water temperature a thermostatic water bath is used.

After the condensation process the liquid refrigerant flows into the accumulator, serving as a refrigerant buffer. The accumulator is supplied with a parallel sight glass for inspection.

Liquid refrigerant leaves the accumulator to the filter/dryer. After the filter/dryer the mass flow rate of the refrigerant is measured with a Coriolis type mass flow meter. This mass flow meter is very accurate in the low flow range, which occurs in this measurement set-up. Errors are smaller than 1 % of the measured value, even at the lowest flow rate (0.1 g/s).

The temperature of the refrigerant just before the expansion process is being controlled by the subcooler. To cool down the refrigerant after the condenser to a desired temperature a thermoelectric element (Peltier)

is being used. By adapting the DC supply voltage to this element the heat transfer capacity can be changed. A software PID controller is used to control this process.
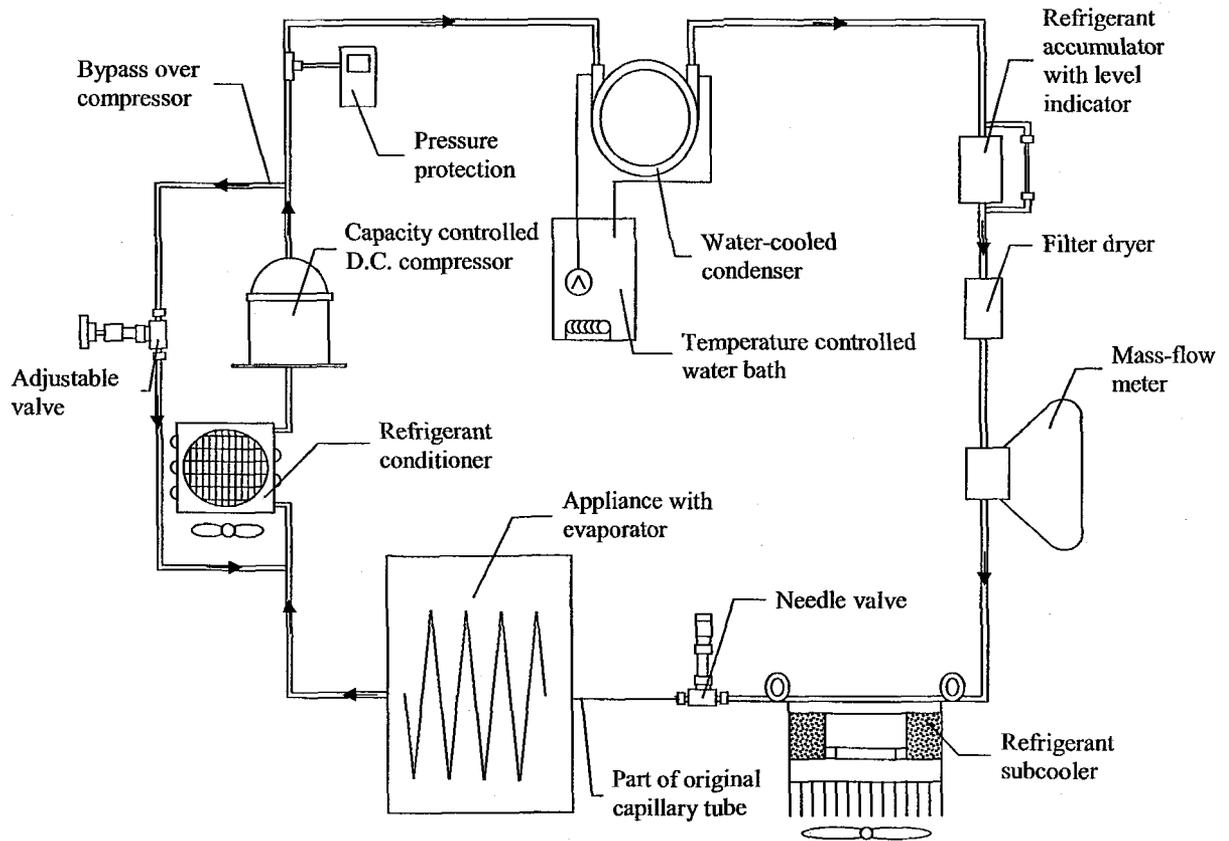

Fig. 2: Schematic outline of the Evaporator Calorimeter.

The hand adjustable needle valve, together with a part of the original capillary tube of the appliance, takes care of the refrigerant expansion. In this way a wide range of superheat temperatures can be set at the end of the evaporator. The reason that a part of the original capillary of the appliance is used is because it is needed to connect the needle valve to the evaporator. Mostly it is not possible to place the needle valve directly before the evaporator, for example because the evaporator is foamed in into the appliance wall. In such cases, using a part of the existing capillary gives an easy access to the evaporator. However, this combination directly brings a problem. It is namely necessary that the refrigerant during the expansion in the needle valve stays in the liquid phase because otherwise gas bubbles will form at the capillary inlet and strongly reduce the volume flow. So for each measurement an appropriate part of the original capillary has to be used in combination with a correct setting of the needle valve. Another problem of the needle valve itself is that due to the needle becoming dirty, the opening of the valve could decrease within a measurement, which causes instability. To prevent the needle becoming dirty the system has to be kept extremely clean and adequate filter/dryers are needed.

The evaporation takes place in the evaporator of the appliance being measured. It is possible that the refrigerant does not completely evaporate in the evaporator (e.g. during stabilisation, mistakes made in the

setting of the needle valve, etc). To avoid liquid refrigerant entering the compressor a refrigerant conditioner is placed before the compressor. This refrigerant conditioner exchanges heat with the ambient air and assures that the refrigerant is always completely evaporated before entering the compressor.

To calibrate the system a calibration unit has been integrated into the system. This calibration unit (see Fig.3) consists of a very well insulated vessel filled with a secondary refrigerant. Inside the vessel a tube has been mounted, which serves as the evaporator (instead of the evaporator of the appliance). An electrical heater has been placed inside the vessel as well. The evaporator exit temperature is indirectly controlled by the electrical heater, which controls the secondary refrigerant temperature in the vessel. The secondary refrigerant evaporates by the heat absorbed from the element and condenses again on the evaporator. The heat absorbed by the evaporator must be equal to heat from the heating element (minus the residual heat transfer with the ambient) when the temperature of the secondary refrigerant and the vessel are constant. This structure shows large similarity with the secondary fluid type compressor calorimeter (Method A, ISO 917 /1/). Subsequently by comparing the power supplied to the element and the cooling capacity calculated by multiplying the enthalpy difference with the mass flow, the system is calibrated. Performing this calibration, for example at 50W cooling capacity, errors in the capacity measurement smaller than 2 % were obtained.
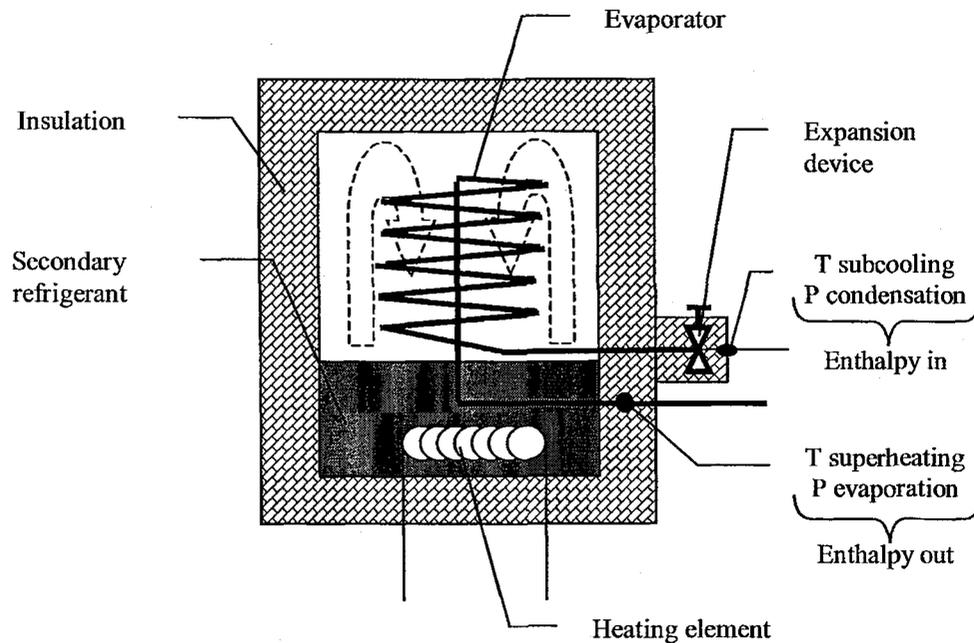
Fig.3: Calibration unit

The accuracy of the UA-values of appliances are within 2.5 % depending slightly on the heat transfer. The accuracy of the UA-values of evaporators depends on the type of evaporators being measured. In the evaporator UA-value not only the accuracy of the heat transfer plays an important role but also the accuracy of the temperature difference between evaporation and air temperature. This temperature difference can be as large as 25 °C for refrigerators down to 4°C for no frost evaporators. With an accuracy of 0.1°C on this temperature difference measurement this leads to errors of 0.5 to 2.5 % in addition to the error in the heat transfer measured. So in general for the UA-value determination of the evaporators an accuracy between 2.5 and 4.5% is obtained.

CONTROL ALGORITHMS

The evaporator calorimeter in most cases is used to compare the performance of different evaporators in the same appliance. To make a proper comparison it is very important that the refrigerant condition in the evaporator is equal for each measurement. The entrance condition is determined by the subcooling temperature and the condensation pressure. The other two important conditions that have to be kept constant are the evaporation pressure and the superheat at the evaporator exit. There are, in fact, two factors that influence those parameters, namely the compressor capacity and the expansion valve setting. For example, running the compressor at constant capacity and increasing the opening of the expansion valve will cause the superheat at the evaporator exit to decrease and the evaporation pressure to increase. On the other hand when the expansion valve is kept in constant position and the capacity of the compressor is increased the evaporation pressure will decrease and the superheat at the evaporator exit will increase. The latter is caused by the fact that the refrigerant in the evaporator has a lower temperature, therefore will absorb more heat and will completely evaporate earlier in the evaporator.

Having explained these basics the three different control algorithms used in the evaporator calorimeter can be made clear:

1. Controlling the evaporation pressure (temperature).
2. Controlling the superheat at the evaporator exit.
3. Controlling the average appliance temperature.

As mentioned in the previous chapter, the expansion valve is a hand adjustable valve, while the compressor is capacity controlled using a software PID controller. This means that putting the expansion valve in a certain position (by hand) it is possible to control either the evaporation pressure or the superheating by controlling the compressor. The other parameter is a consequence of the position of the expansion valve. Next to these two control algorithms a third one exists. It is namely also possible to control the average appliance temperature using the compressor variable capacity. This is easy to explain because the appliance temperature is actually determined by the evaporation pressure (temperature) and the superheat in the evaporator. Considering the first two control algorithms there is always one degree of freedom, the evaporation pressure or the superheat at the evaporator exit. This parameter has to be set manually using the expansion valve. For comparing different measurements the uncontrolled parameter also has to be constant for each measurement. As it is very difficult to set identical values by hand for each measurement, mostly two measurements are performed and an interpolation is made. It has been proven to be quite complicated to control all the different parameters accurately because each control loop affects another one.

For each different measurement series it is possible to select the easiest control method. For example in a domestic freezer the superheat at the evaporator exit is very small (because the temperature difference between the evaporator and the cell is small). In these tests it is very difficult to set a certain superheat by hand. In that case the compressor speed can be used to regulate the superheat; the position of the expansion valve, which has to be set manually, determines the evaporation pressure. In refrigerator measurements the superheat at the evaporator exit is much larger. In that case it is easy to set the superheat by adjusting the expansion valve. The compressor can now be used to keep either the appliance or the evaporation temperature constant.

Currently it is being examined if it is also possible to use any type of regulated expansion devices. The easiest would be to use a thermostatic expansion valve to control the superheat at the evaporator exit and to use the compressor to regulate the evaporation pressure. However a thermostatic expansion valve for such low capacities is not available on the market. Another possibility, which seems more promising, is the use of a similar needle valve as used in the present measurement situation, but operated by means of a servo. It needs recognition that implementing the additional control loop (for the expansion valve), which interferes with the other control loops, is not a straightforward task. Stability problems caused by the sensitivity of the system, in particular due to the small mass and heat flows involved, can be expected.

THE DATA ACQUISITION AND CONTROL SYSTEM

To record all measurement data from the thermocouples, pressure transducers and the massflowmeter, a data acquisition system connected to a personal computer is used. LabVIEW /2/ is used as data acquisition software. The data acquisition system in the first place has channels for measuring the subcooling, superheating, ambient and appliance temperatures and evaporation and condensation pressures. Next to these channels over 20 spare channels remain, which can be used to measure extra temperatures on the evaporator, appliance walls, doors etc. The latter can be used to make more complicated studies of heat flows in the appliance. It is, however, also possible to make more pressure measurements, for example to study the pressure drop in an evaporator.

The LabVIEW /2/ software also contains the PID controllers to regulate the compressor, the subcooler and the heating element of the calibration unit simultaneously. The use of software PID controllers makes the system very flexible. For example, it is very easy to switch between the three different compressor control algorithms described in the previous section. As input for the controller it is easy to switch between the evaporation temperature, the superheat or the average appliance temperature. This would be different if complicated hardware PID controllers would have been used since these would require physically different connections.

MEASUREMENT EXAMPLE

In a refrigerator as presented in Fig.4, the heat transfer from the appliance inner-liner takes place by radiation directly to the evaporator (and, if present, to the shelves, baskets and to the products in the cabinet) and convection. In the measurements described in this paragraph the effect of changing the radiation coefficient of the walls and the evaporator on the heat transfer is being examined.

The assumption was that by decreasing the emission coefficient of the inner-liner of the appliance the heat transfer from the inner walls surface would also decrease and that therefore the surface temperature would increase with respect to the appliance temperature. Such a higher inner-liner temperature would cause a smaller temperature difference between ambient and inner-liner and therefore a smaller heat flow into the appliance. So by decreasing the emission coefficient of the walls the thermal resistance of the appliance walls would improve. On the other hand, the heat transfer to the evaporator also consists of radiation and convection. By decreasing the radiation effect to the evaporator the overall heat transfer coefficient of the evaporator would also decrease. With a lower heat transfer coefficient the temperature difference between the evaporator and the air would have to be increased to create the same heat flow. Fig.4 schematically shows the expected temperature profiles following these assumptions. The thick line shows the expected temperature profile in the normal situation and the dashed line shows the assumed temperature profile when the radiation is being decreased (the dashed line is shifted a little above the thick line for a better readability).

The evaporator calorimeter is the ideal instrument to perform some experiments with these radiation differences because it is able to measure the heat transfer of both the evaporator as well as the insulation.

In the experiment performed a small table-top refrigerator with a foamed-in evaporator without any shelves or baskets was used. In this appliance the air temperature was measured using three thermocouples soldered in copper cylinders as typical in standard appliance tests /3/. The cylinders were wrapped with aluminium tape (low emission/absorption coefficient) to avoid radiation effects on the air temperature measurement. Also different temperatures on the appliance walls and ambient temperatures were being measured. First a base line test was performed without making any adaptations to the appliance.
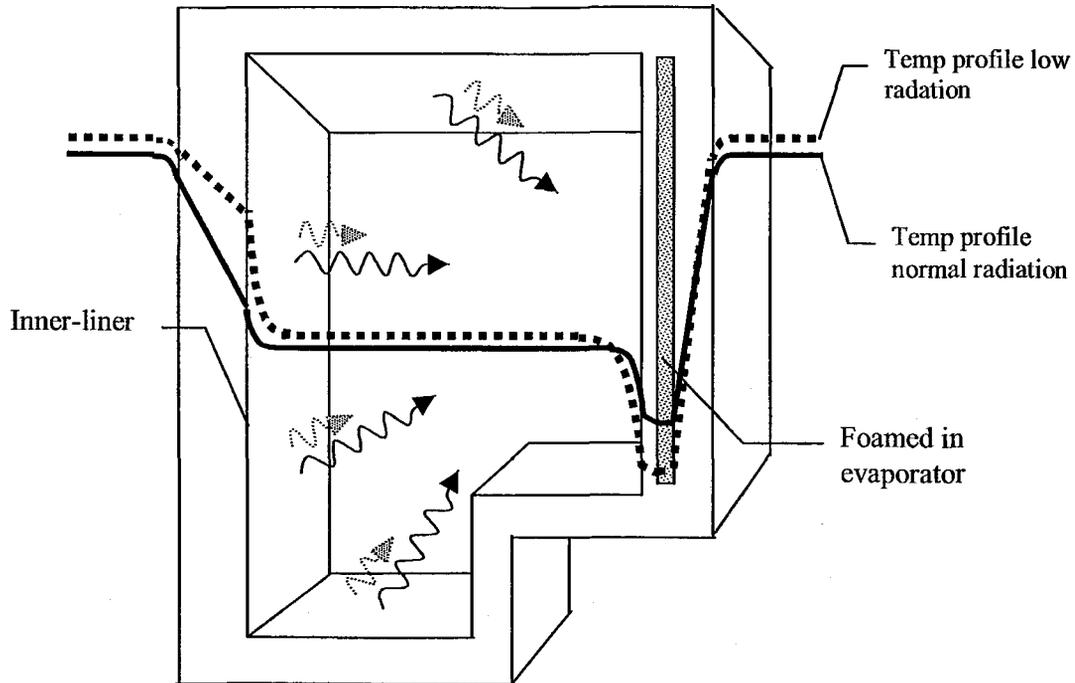
Fig.4: *Temperature profiles in a refrigerator cabinet*

In a second test aluminium tape was used to cover the walls of the appliance except for the evaporator wall. The radiation coefficient of the original inner liner is expected to be approximately 0.8, while the radiation coefficient of the aluminium tape is expected to be at maximum 0.2. In a third test the evaporator was also covered with aluminium tape. (It is assumed that the aluminium tape does not influence the conductive heat transfer within the appliance wall, because it is a very thin layer only and has a high conductivity.)

The condensation temperature, the temperature before expansion and the ambient temperatures were kept constant at the values indicated in Table 1. For this measurement the compressor was used to control the evaporator superheating (control algorithm 2). It was kept constant at the value indicated in Table 2. The cell temperature of the three measurements was also kept constant by manually adjusting the expansion valve.

Ambient temperature	25.0+/-0.1 °C
Condensation temperature	47.0+/- 1°C
Temperature before expansion	26.0+/- 1°C
Superheating	12.0+/- 1°C

Table 1: *measurement conditions*

Table 2 shows the main results of the three tests. Comparing the baseline measurement with the measurement in which the walls were taped it can be seen that the heat transfer coefficient of the appliance indeed decreased (with 4.1%) by reducing the radiation from the walls. The heat transfer coefficient of the evaporator, however also decreased (with 9.9%).

Comparing the measurement in which both the evaporator and the walls were taped with the baseline measurement, the effect on the heat transfer coefficient of the evaporator is even larger. It decreased with 23%. The heat transfer coefficient of the appliance, however, increased (4.7%). This at first seems very strange. A possible explanation for this is that the direct heat transfer to the evaporator (the heat transfer

from the back wall directly to the evaporator) has increased significantly because of the reduced evaporation temperature.

	Baseline test	Decreased radiation coefficient off walls	Decreased radiation coefficient of walls and evaporator
T average cell [°C]	0.3	0.4	0.5
T evaporation [°C]	-21.7	-23.0	-29.1
T average inner-liner [°C]	2.6	4.9	4.6
T ambient – inner-liner [°C]	22.4	20.1	20.4
T cell –T evaporation [°C]	22.0	23.4	29.6
T inner-liner – T cell [°C]	2.3	4.5	4.1
T ambient – T cell [°C]	24.7	24.6	24.5
T ambient – T evaporation [°C]	46.3	48.0	54.1
Q evaporator heat [W]	42.3	40.4	43.8
UA-value evaporator [W/K]	1.92	1.73	1.48
UA-value appliance [W/K]	1.71	1.64	1.79

Table 2: measurement results

It is clear that decreasing the emission coefficient of all inner walls of the appliance will certainly not have a positive influence on the energy efficiency of the appliance. Decreasing only the emission coefficient of all inner walls except the evaporator has a positive effect on the heat transfer coefficient of the insulation but a negative effect on the evaporator heat transfer coefficient. Though this has not been evaluated here, the total effect on the efficiency of the appliance may also be negative.

A complete theoretical analyse of these results would fall outside the scope of this paper, which is mainly the presentation of the measurement set-up. The measurement performed, however, is a good example of the possibilities of the Evaporator Calorimeter.

CONCLUSIONS

In this paper the difficulties which had to be overtaken to build an Evaporator Calorimeter are indicated. The main difficulty is the low heat transfer, which has to be measured accurately. For the purpose of measuring the refrigerant flow a very accurate Coriolis flow meter has been used. To calibrate the system a calibration unit has been manufactured, which is able to calibrate the system by means of a heat flow balance between an electrical heater and an evaporator in an insulated vessel. Also for regulating the refrigerant flow through the system special measures have been taken. A variable speed compressor is used in combination with a bypass to be able to create a wide range of capacities. The condensation, subcooling, evaporation pressure and superheat can all be regulated with different control loops. Using the evaporator calorimeter it is possible to perform complicated tests on all kinds of evaporators under different conditions. At the same time it is possible to perform tests on the insulation of the refrigerating appliance and study all kind of adaptations. In the paper an example of the evaluation of radiation effects in a refrigerator is used to show an example of one of the possibilities of the system.

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