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To Increase the Characteristics of Cooling System And Plate Evaporator of a Household Refrigeration System

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Abstract: *This thesis is based on the characteristics of the cooling system and plate evaporator of a household refrigerator. Through these articles, knowledge is provided that can be used to increase the operational efficiency in household refrigeration. The heat transfer and pressure drop in a commonly used free convection evaporator – the plate evaporator focused on Part A, B and C. Improvement of energy efficiency is totally based on the different stages and parts like that part A, B, C, D, E,F and G. All parts have a phase to demonstrate the parts of involvement of increasing the efficiency of the refrigeration system. Applicable correlations are suggested on how to estimate the air side heat transfer, the refrigerant side pressure drop and the refrigerant side heat transfer. This piece of examination the stream bubbling warmth move in a family unit cooler evaporator with level stream, continuous twists and a non□circular cross area. Trials were directed on a "cut out" of the contextual analysis fridge plate type evaporator. It results in recommendations on how to optimize the capillary tube length and the quantity of refrigerant charge. In portion of G the topic "charging and throttling" is investigated in an unparalleled experimental study based on more than 600 data points at different quantities of charge and expansions device capacities. The charge distribution in the cooling system at transient and steady state conditions hold a unique experimental study of the refrigerant in Part D, E and F. From this cyclic losses are identified and estimated and ways to overcome them are suggested.*

Keywords: Optimization, Refrigerator, Domestic refrigerator, Free convection, Plate evaporator, , Pressure drop, Two□phase, Cooling system, Charge inventory, Cyclic losses, a parametric, Performance Standards, producers, temperature, efficiency, freezer, Surface drying, pathogens, configurations, heat exchanger, evaporator, mineral.

I. Introduction

Domestic and household refrigerators and freezers are found in almost every home in the industrialized parts of the world and in increasingly larger number elsewhere. It is estimated that the global annual production is more than 90 million units in 2009. In Asia the annual production is about 45 million units with China alone accounting for more than 30 million units. Production in Europe is around 25 million units and North and South America is about 20 million units a year.

With an expected lifetime of 10 to 20 years the stock of household refrigerators and freezers operating in this moment is more than one billion units. Evidently this gives a significant impact on the global energy consumption. The department of energy in the U.S.A. estimated that household refrigeration is responsible for 7.2 % of the average household energy consumption 2011. Melo and Silva estimated that about 6 % of the produced electrical energy is used by household refrigerators and freezers worldwide (Negrao and Hermes, 2011). Thus, it is not surprising that household refrigeration is a target for energy consumption controls in the EU and in many countries around the world.

Internationally, there are about 60 countries worldwide that have some sort of program to regulate the energy efficiency of refrigerators and freezers, mostly in the form of mandatory comparative energy labelling and Minimum Energy Performance Standards (MEPS). These programs have proven to be an effective tool to reduce the energy consumption (Mahlia and Saidur, 2010). Within Europe, the European commission directive of 1994 (94/2/EC) made it compulsory to energy label household refrigerators and freezers. The objective with this was to encourage consumers to favour appliances and equipment with high electrical efficiency, thus encouraging the producers to improve the efficiency of their appliances. Furthermore, in the directive of 1996 (96/57/EC) on energy efficiency requirements, the most energy consuming units were banned. For the producers the message was clear: energy efficiency is important!

From the second law of thermodynamics it is known that the efficiency of a heat pump system, which is the key technology used in household refrigeration, depends on the temperature levels at the cold side evaporator and the warm side condenser. A higher evaporation temperature or a lower condensation temperature gives higher system efficiency. In other words, a smaller *temperature lift* from the cold to the warm side increases the system efficiency. This also means that the efficiency of the heat exchangers, in terms of operating with small temperature differences, is important for the overall efficiency. The governing equation for the ideal Carnot cycle operating as a cooling machine is:

$$COP_{Carnot} = T_2 / T_1 \square T_2$$

Where T is temperatures in Kelvin and 1 and 2 denotes the temperatures at the high and low temperature side. *COP* stands for Coefficient of Performance which, for a cooling machine, is defined as the ratio between the useful cooling energy and the needed work:

$$COP = \frac{Cooling\ energy}{Work}$$

II. Aim and Scope

The purpose of this work is to provide knowledge that can be used to increase the operational efficiency in household refrigerators and freezers. The focus has been the attributes of a free convection plate evaporator and of the cooling arrangement of a family cooler. For the evaporator, the worry was to discover appropriate connections to foresee heat move and pressing factor drop; inside in the refrigerant cylinder and remotely on the air side. For the cooling framework a superior agreement all in all was looked for in view of some key inquiries.

III. Research Methodology

The results of this thesis are mainly based on experimental work. Pure simulations using state of the art tools (FEMLAB) were also used, but to a lesser extent. At an early point in the research project it was decided to use one type of household refrigerator as a case study. Most experiments were therefore conducted on this refrigerator, more or less modified for the experiments. The Electrolux refrigerator ER8893C can be described as a free convection, cycle defrost, on-off controlled, single door, upright, all refrigerator.

Ordinarily a cooler has lower vanishing temperature and higher limit than an unadulterated fridge. Various kinds of warmth exchangers are additionally utilized (constrained convection and free convection). Along these lines, much of the time it is conceivable to make general determinations from the contextual analysis results that are pertinent for the entire field of family refrigeration.

In short this means that no fans are used at the heat exchangers, that defrost occurs when the compressor is at rest without additional heating and that temperature is controlled by the compressor simply switching on and off. The reason for selecting this refrigerator as the case study test object was that it was a common product on the Swedish and European market. Obviously such decision is always open for criticism.

Different experimental studies were conducted; flow visualization of the refrigerant flow through an observation glass evaporator, thermo-graphic study of the overall cooling system including the heat exchangers, heat transfer and pressure drop measurements in the evaporator, heat transfer measurements at the evaporator air side, charge inventory at different parts of the cooling system, parametric study of varied refrigerant charge and expansion device capacity. In one case a separate experimental setup with an isolated test section was used. This was to measure the refrigerant side heat transfer which called for a more controlled environment. The most important results of the various experiments were published in reviewed journal articles and conferences relevant to the research field.

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IV. Configurations in Household Refrigeration

Household refrigerators & freezers are thermally insulated compartments in which food can be stored at reduced temperatures hereby extending the shelf life. The refrigerator (or fridge) has a storing temperature above 0 °C (typically 0 to 10 °C) making it suitable for fresh food and vegetables. The freezer has a temperature below 0 °C (typically 6 to 18 °C) making it suitable for frozen food and longer storing times. Normally, there also exist special purpose compartments within the refrigeration unit to provide a more suitable environment for storage of specific food. For example, a warmer compartment for maintaining butter is often found in the refrigerator door. A high humidity compartment for vegetables and fresh food are also common in a refrigerator.

Refrigerators and freezers are available in several styles. All freezers can be found as upright freezer or as chest freezer. Combinations of refrigerators and freezers can be found as top freezers, bottom freezers, side by side or as a separate freezer compartment located within the larger refrigerator compartment. All refrigerators, which the case study in this work is an example of, are typically upright[3].

The configurations vary considerably by region, but at a global level, top freezers are the most common (nearly 38 %), bottom freezers are next at about 33 % and side by side combinations are about 15 %. The remaining types are mostly all refrigerators or other configurations including separate freezer compartments (Harrington, 2009). Qualities that are desirable in a good cabinet are, according to the ASHRAE handbook (2010):

1. Maximum food storage volume for the floor area occupied by the cabinet
2. The best in utility, performance, convenience, and reliability
3. Minimum heat gain
4. Minimum cost to the consumer

The refrigerator used in the case study:

ER8893C is a single compartment upright household all refrigerator. The declared energy consumption is 0.78 kWh/21h(energy class B). It has the following typical data (Small variations occurred with different specimens used in the experiments. Consult the various papers for a more detailed description):

- Cabinet: (External dimensions: 1.75 □ 0.6 □ 0.6 m and 0.04 m wall thickness), 350 l internal volume, UA value 2.3 W/K.
- Evaporator: Free convection, (0.66 □ 0.49 □ 0.0014 m), aluminium, plate type, back wall located (20-25 mm distance to back wall), integrated downstream located accumulator. Refrigerant line length (including accumulator) 6.02 m. Internal hydraulic diameter 3.2 mm. Total internal volume 114 ml whereof accumulator volume 46 ml in which approximately half the volume can store liquid at steady state condition. UA value about 3.7 W/K.
- Condenser: Free convection, (1.33 □ 0.51 □ 0.008 m), steel, wire on tube (53 vertical wires on each side of the tubing, each of diameter 1.5 mm) positioned with 25 mm distance to the cabinet back wall. The refrigerant flow is horizontally downward (see Figure 9). Internal volume 135 ml. Internal/external tube diameter 3.5/5.0 mm. UA value about 7.7 W/K (condenser in original location and cabinet located against a wall)
- Capillary tube expansion device (2.54 m length and 0.60 mm internal diameter) with coaxial type suction line heat exchanger of 2 m length.
- Filter drier: Molecular sieve with internal free volume 11.3 ml.
- Refrigerant: Nominal refrigerant charge 33 to 36 g of Iso-butane (R600a)
- Capacity control by intermittent run (on- off cycling) with self-defrosting in every off cycle.

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Figure 1: Household refrigerator ER8893C front and backside.

In Figure (left picture) the plate type, free convection, semi hidden evaporator is located at the upper part of the back wall in the cabinet. The picture to the right shows the condenser and the compressor at the refrigerator back side. Both pictures include some experimental equipment (thermocouples and pressure transducers).

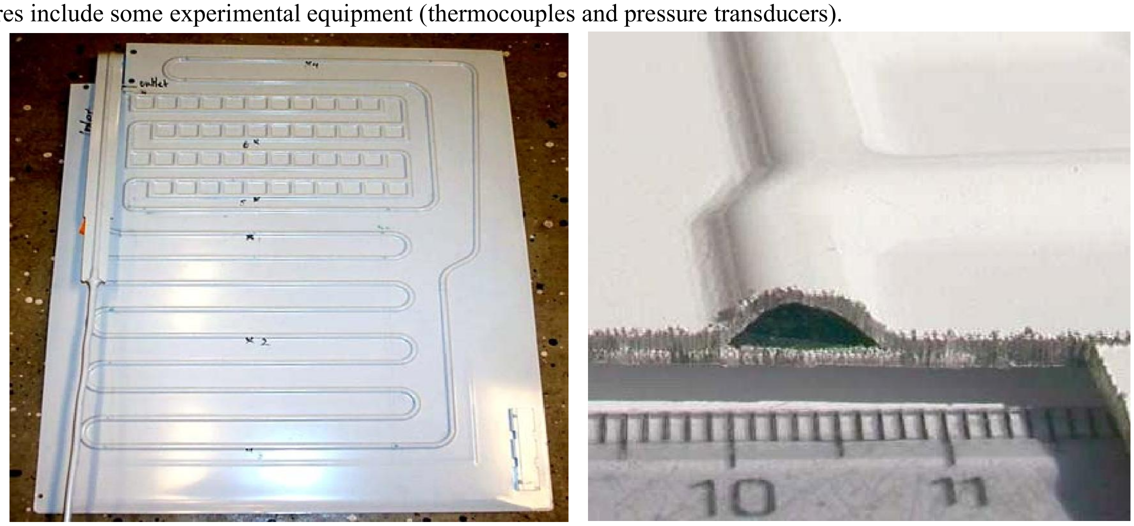
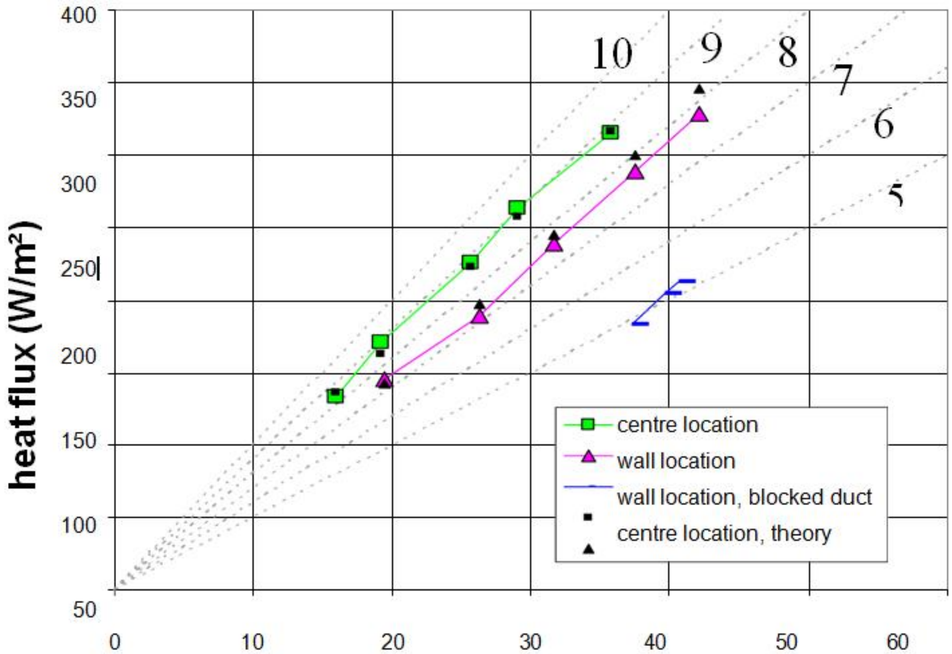


Figure 2: The left picture shows the plate evaporator back side with its integrated refrigerant channels. At the left side in this picture the capillary tube suction line heat exchanger (that connects the evaporator to the cooling system) is visible. The right picture depicts a close- up of the refrigerant tube cross section.

V. PART- A: AIR SIDE HEAT TRANSFER OF A DOMESTIC REFRIGERATOR PLATE-TYPE EVAPORATOR

This portion the thesis concerns the air side heat transfer of the case study refrigerator plate evaporator. Experiments were conducted in the refrigerator at steady state dry air conditions by varying the evaporator location and by varying the surface emissivity. The purpose was to find applicable heat transfer correlations and to see the influence of different evaporator locations.

Firstly, the evaporator was located in the centre of the refrigerator cabinet to give an unrestricted flow around the vertical evaporator. The results should indicate the highest possible heat transfer using the given evaporator at free convection conditions. Then, the evaporator was placed in its original position with a 25 mm distance to the back wall. Finally, the air duct behind the evaporator (formed by the evaporator, the back wall and a 25 mm part of the side walls) was blocked in order to see its influence of the heat transfer.



Graph 1: Temperature difference t-air – t-evap (K)

As was expected Figure 12 shows that the highest heat transfer coefficient(about 8.8 W/m² K) was observed when the evaporator was located in the cabinet's centre. When the evaporator was in its original location (wall location), the heat transfer coefficient decreased to about 7.6 W/m² K. When the air duct behind the evaporator was blocked the heat transfer coefficient decreased to about 5.1 W/m² K (both sides of evaporator used as calculated area in all cases).

As was expected Figure shows that the highest heat transfer coefficient (about 8.58 W/m² K) was observed when the evaporator was located in the cabinet's centre. When the evaporator was in its original location (wall location), the heat transfer coefficient decreased to about 7.6 W/m² K. When the air duct behind the evaporator was blocked the heat transfer coefficient decreased to about 5.1 W/m² K (both sides of evaporator used as calculated area in all cases).

The figure also shows the estimated heat transfer coefficients (marked "theory" in the plot) which are the sum of the estimated free convection heat transfer and the estimated thermal radiation heat transfer. In all cases conventional black body radiation equations were used. For the centre located evaporator the Churchill and Chu correlation (Incropera and DeWitt, 1996) was used to estimate the free convection heat transfer. As can be seen, the estimated results are in good agreement with the experimental results. For the wall located evaporator, the free convection heat transfer of the evaporator front and back side was estimated in different ways to reflect the different flow conditions at each side. On the front side the Churchill and Chu correlation was used. On the back side the vertical channel correlation proposed by Bar□Cohen and Rohsenow (Incropera and DeWitt, 1996) was used[5]. As can be seen in the figure, in this case the estimated results were somewhat over predicted. The explanation to this deviation and the lower heat transfer for the wall located evaporator compared to the centre located is discussed in the following section.

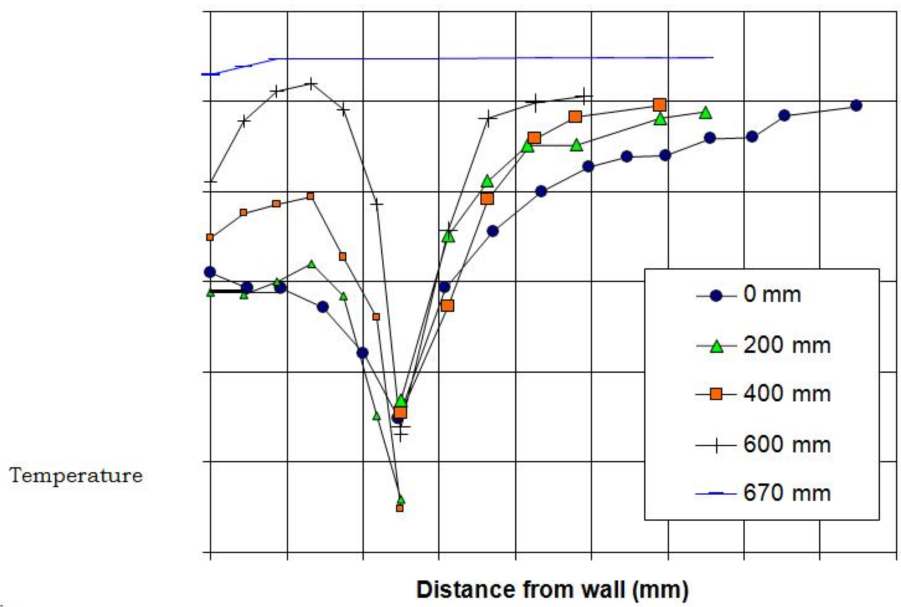


Figure 3: Air and surface temperatures vs. distance from wall for different elevations.

VI. PART B: FLOW BOILING HEAT TRANSFER AT LOW FLUX CONDITIONS IN A DOMESTIC REFRIGERATOR EVAPORATOR

This portion of the thesis is to investigates the flow boiling heat transfer in a refrigerator evaporator with horizontal flow, frequent bends and a non□circular cross section. Above figure shows the test section. Experiments were conducted on a "cut out" of the case study refrigerator plate type evaporator. The test section, that was electrically heated, was connected in series with a pre heater so that the inlet vapour quality could be varied. The mass flux was varied between 21 and 43 kg/m²s, the average heat flux between 1 and 5 kW/m² and the vapour quality between 0.2 and 0.8 (flooded outlet conditions).

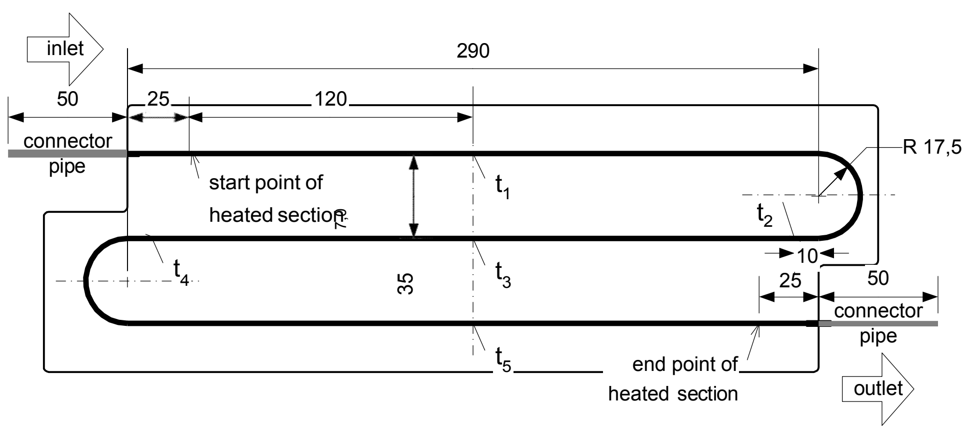


Figure 4: Test section which is a cut out from the case study refrigerator evaporator.

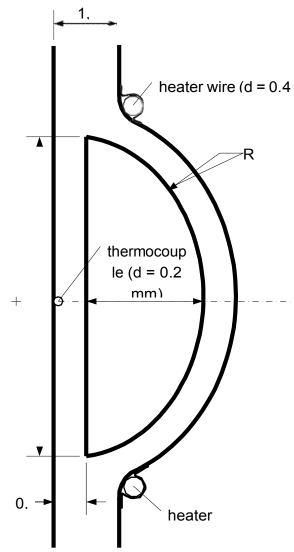


Figure 5: Refrigerant tube cross section

The flow pattern was predicted using the flow maps suggested by Kattan et al. (1998).

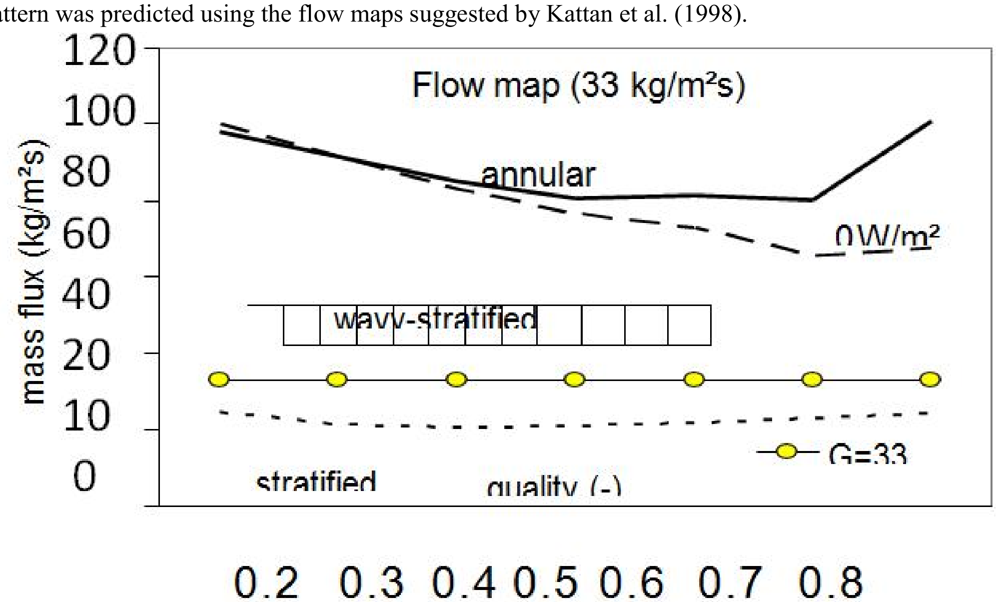


Figure 6: Example of flow map calculated at 33 kg/m²s Note that this flow map is not general for all mass fluxes.

VII. PART C: PRESSURE DROP IN A PLATE EVAPORATOR FOR REFRIGERATORS

The purpose of this experimental study was to find an applicable correlation to estimate the two□ phase pressure drop in household refrigeration evaporators. The case study plate evaporator, used for the experiments, was fitted with 16 pressure taps along the refrigerant tube to give an extensive picture of the pressure drop distribution, including the pressure drop over bends. The pressure tap locations are seen in Figure 18. The test conditions are displayed in Table 1 and the experimental results are shown in Figure 19.

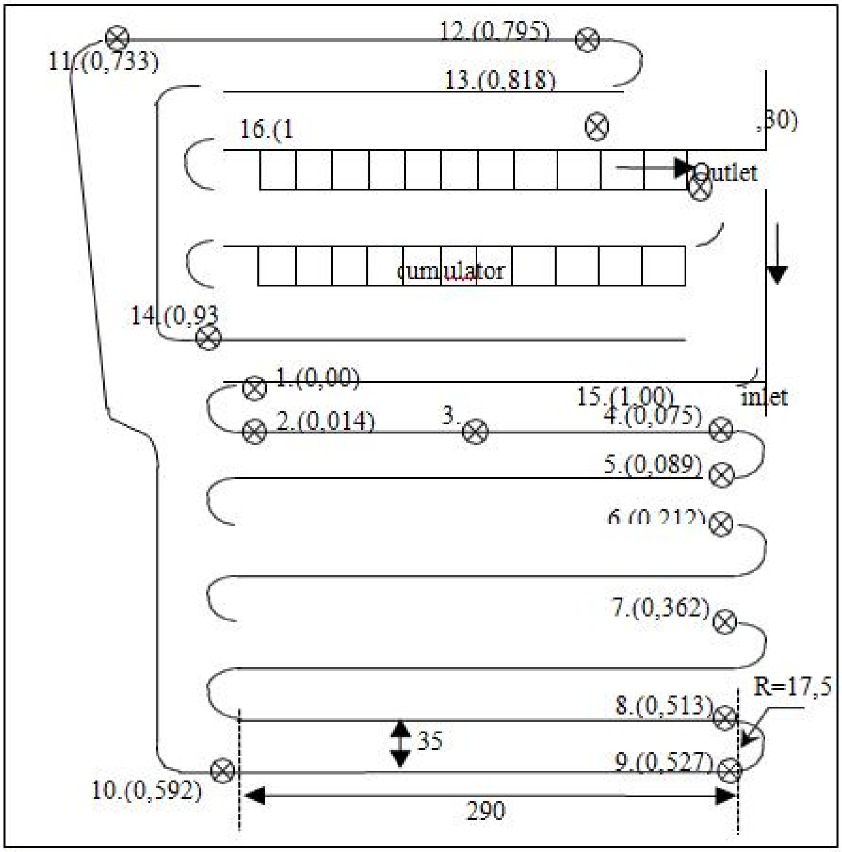


Figure 7: Pressure tap locations at the evaporator. Relative length is given within parentheses. The relative length is the fraction of the distance from just upstream of the first bend to the inlet of the accumulator.

Nr	t_2 (°C)[1]	t_1 (°C)[2]	*mass flow* $\dot{m}$ *(g/s)*	*mass flux G* *(kg/m²s)*[3]	*inlet vapour quality* *x (-)*[4]	*cooling capacity* $\dot{Q}$ *(W)*[5]
1	-23.1	39.5	0.280	20.34	0.136	94.1
2	-19.7	41.8	0.331	24.03	0.134	111.0
3	-14.0	45.3	0.428	31.10	0.126	143.0
4	-9.3	48.5	0.519	37.67	0.127	172.2
5	-4.3	51.9	0.627	45.50	0.132	205.8

Table 1: Test conditions

Notes:

1. Saturation temperature from averaged pressure, position 1 to 15.
2. Saturation temperature from condenser pressure.
3. Mass flow divided by cross section area 13,774mm².
4. Calculated from enthalpy at condenser outlet minus enthalpy change over capillary-suction line heat exchanger.
5. Calculated as the product of the refrigerant mass flow and the enthalpy change from evaporator inlet to outlet.

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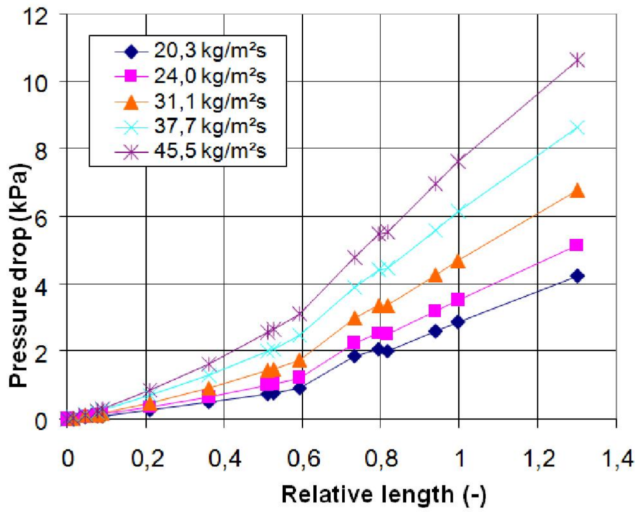

Figure 8: Pressure drop along the refrigerant tube at different mass fluxes

This corresponds to an efficiency loss of at about 1-2 %. These resistances should be added to the get the total the[redacted]easured the temperatures and pressure drop over the heat exchanger and the suc[redacted]ator pressure drop is higher at the eight first minutes in the on-cycle. This is the tim[redacted]ne in on-cycle for refrigerant to fill up the evaporator) and thus the time when sup[redacted]e drop is less than 50 mbar (5 kPa) in the later on-cycle. It is interesting to note that[redacted]e is almost as large as in the evaporator. This is a loss corresponding to almost 1 K, which, calculated into an efficiency loss is about 2-3 %. The main contributions of this work are:

- Correlations are suggested on how to calculate heat transfer and pressure drop in a household refrigerator evaporator.
- A potential to increase the efficiency by about 10 % was revealed at the air side by changing the flow and radiation conditions around the evaporator.
- Thin film evaporation at tube walls repeatedly wetted by liquid plugs was suggested to be the physical explanation to the unexpectedly high boiling heat transfer coefficients observed. This view challenges conventional in□tube evaporation knowledge.
- A new method was developed on how to measure refrigerant charge at different locations in the cooling system.
- Charge distribution was measured at transient and steady state conditions from which a new understanding of the system operation was achieved. Cyclic losses were estimated based upon the experimental data.
- The subject of “throttling and charging” was systematically investigated. Results indicate insensitivity for a wide range of settings.
- Experimental evidence suggests that the capillary tube mass flow is very sensitive to the inlet condition when the refrigerant is nearly saturated. It is sharply reduced when the subcooling disappears and vapour enters its inlet. This effect appears to be a key mechanism for quick charge redistribution at start□up and for a stable charge distribution at varied thermal conditions.
- The cyclic losses were estimated to be 8 % (efficiency) for the studied refrigerator. In order to reduce these losses it was suggested to modify the evaporator channels into a downward inclination and to use smaller diameter at the upstream part.
- Suggestions are made on how to increase the efficiency (1□2 %) at steady state conditions by moving the refrigerant channels closer to the evaporator edges. Short cycling was found to increase the efficiency about 4.5- 5.0 %.

IX. CONCLUSION

In the first part of this thesis the objective was to find applicable correlations on how to calculate heat transfer and pressure drop for a household refrigerator evaporator. The suggested correlations are presented in papers A, B and C. The air side convective heat transfer can be estimated by the correlations suggested by Churchill and Chu (3) and Bar Cohen and Rhosenow (4), (see also chapter 3 and Paper A for details):

Overall, it is clear that the largest thermal resistance is at the evaporator air side for a plate type evaporator. For instance, at the air side the overall heat transfer coefficient was approximately 8 W/m²K (Part A). On the refrigerant side it was about 4 kW/m²K (Part B) or about 500 times higher12. It follows that a larger potential for energy saving exist in the temperature difference at the air side than on the refrigerant side. It was for instance shown in paper A (and supported in chapter 4, Figure 42) that there is a potential to lower the energy consumption by about 10 % if the evaporator is oriented differently. Even if this potential was found when the evaporator was positioned freely in the middle of the refrigerator cabinet, which is a highly impractical solution, it clearly indicates that the evaporator backside is poorly used for heat transfer. The same paper (A) showed that the heat transfer degradation at the evaporator backside was a result of restricted air flow and decreased thermal radiation. There are most likely possibilities here for design modifications that will give higher system efficiency.

The second part of the thesis focused on the overall cooling system.

In Portion D the development of a new and fully automatic method intended for charge inventory measurements was described. It was shown that this method is accurate and that it gives large time savings for repetitive measurements.

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