VISUALIZATION OF THE REFRIGERANT FLOW AT THE CAPILLARY TUBE INLET OF A HIGH EFFICIENCY HOUSEHOLD REFRIGERATOR

Santiago Martínez-Ballester *, Laetitia Bardoulet, Alessandro Pisano, José M. Corberán

Universitat Politècnica de València, Institute for Energy Engineering. Camino de vera, s/n, Valencia, 46022, Spain

*Corresponding Author. Tel.: +34 963 879 120 E-mail address: sanmarba@gmail.com (S. Martínez).

ABSTRACT

Subcooled conditions at the condenser outlet ensure complete condensation, which is necessary to increase the cooling capacity and ensure the liquid conditions at the expansion device inlet in vapor compression systems. However, in household refrigerators, recent works point out the presence of two-phase flow at the capillary tube inlet. These systems behave quite different from others refrigeration systems due to the extreme low capacity. In the present work, a test bench was built to visualize the refrigerant flow at the condenser outlet and at the capillary tube inlet of a household refrigerator. A transparent tube replaces the final part of the condenser and three transparent filters were installed with different orientations. Different positions of the capillary tube in the filters were tested. After analyzing the condenser temperature profile, the results show that for the refrigerator analyzed, the capillary tube was drawing in always a two-phase flow in steady conditions.

Keywords: Household refrigerator, capillary tube, subcooling, refrigerant visualization

1. INTRODUCTION

Household refrigerators are equipped with capillary tube as expansion device due to its simplicity and low cost. For avoiding the presence of liquid at the compressor inlet when it starts-up and preventing the sweating on the suction line, if its temperature is below the dew point temperature, the capillary tube can be placed in thermal contact with the suction line working as a liquid-to-suction heat exchanger (CT-LSHX). Although CT-LSHX has a quite limited capability to control the system, this solution is widely adopted in household refrigerators, mainly with two different configurations: concentric or lateral tubes (Hermes *et al.*, 2008). Other devices, such as variable expansion valve, may be possible alternatives, but due to the low cooling capacities (around 100 W), they are still not commercially available for household refrigerators (Ronzoni *et al.*, 2013).

CT-LSHX introduces complex phenomena due to simultaneous two-phase flow expansion and heat transfer, such as reverse heat transfer and re-condensation (Bansal and Yang, 2005). Some of the negative consequences of these phenomena are the following: noise (Hartmann and Melo, 2013), which is becoming an important quality issue; flow hysteresis and flow oscillations (Liu and Bullard, 1997); and reduction of the CT-LSHX effectiveness (Liu and Bullard, 1997), which affects the global efficiency. Studies about how to solve the noise problem report that it disappears when there is enough subcooling at the capillary tube inlet (Hartmann and Melo, 2013). This fact also supports the idea that two-phase flow at the capillary tube inlet contributes to the re-condensation phenomenon inside the CT-LSHX. Besides the problem of noise, another important consequence of the liquid absence at the condenser outlet is the loss of global efficiency, due to the reduction of cooling capacity given the same compression work.

Boeng and Melo (2014) performed an experimental study to find the optimal combination of refrigerant charge and capillary tube in a refrigerator-freezer of 403 liters equipped with R600a. For varying the expansion device capacity, they used a larger internal diameter capillary tube in series with a metering valve. Boeng and Melo (2012) complemented the previous work by means of applying a model (Hermes et al., 2008) to develop a correlation between the valve opening degree and the equivalent capillary diameter. They obtained a good prediction of the mass flowrate excepting for the tests with fully open valve or subcooling less than 5 K. By visualization of the capillary tube inlet, Boeng and Melo (2012) concluded that even with a certain subcooling of 5 K, the inlet was two-phase flow. They pointed out as possible explanation that at the capillary inlet there is a non-equilibrium mixture of subcooled liquid and saturated vapor, instead of being purely a liquid phase. Finally, they could evaluate numerically that the vapor quality at the capillary tube inlet ranged between 2-12%, depending on the refrigerant charge.

Inan *et al.* (2003) visualized with X-ray equipment, the filter, the accumulator at the evaporator outlet, and the section at the evaporator inlet in a refrigerator-freezer of 435 liters equipped with R134a. They clearly identified fully liquid conditions at the capillary tube inlet and, in few minutes after compressor start-up, the filter was completely full of liquid. The value for the subcooling was of 5 K when quasi-steady conditions were reached. Thus, regarding the inlet conditions to the capillary tube the observations of Inan *et al.* (2003) are different to those observed by Boeng and Melo (2012). One of the reasons could be the fact of running the system with different refrigerant mass flow rates because of using different refrigerants. In literature, the subcooled conditions at the capillary tube inlet, estimated from measuring the temperature on the wall surface, is always reported, however the cited problems of noise and the conclusions of others works (Hartmann and Melo, 2013; Boeng and Melo, 2012) point out that these conditions maybe are not real. Different reasons may explain it: non-equilibrium between subcooled phase and saturated vapor at capillary inlet or a too small compressor capacity compared with the expansion device capacity of the capillary tube used, what would mean a capillary tube too big for that compressor. This latter factor is becoming more important since nowadays a high efficiency refrigerator-freezer of a volume of 330 liters is consuming a continuous power about only 20 W (0.48 kWh/day).

To deepen in this phenomenon, an experimental work of visualization is clearly needed. To the author's knowledge, there are not specific experimental works focused on the evaluation of the actual condenser outlet conditions in high efficiency refrigerators, which have extreme low capacities. Therefore, the main objective of this work is to assess by visualization the actual conditions taking place at the capillary tube inlet. A novel test bench has been designed in order to visualize and analyze the phenomena occurring at the condenser outlet, along the filter and at the capillary tube inlet.

2. EXPERIMENTAL SET-UP

2.1 Test Bench

The original apparatus is a high efficiency (approximately 0.48 kWh/day) two-door refrigerator-freezer of 330 liters, no-frost, and operating with R600a. It consists of a fin and tube evaporator, a tube and wire condenser and a variable-speed 7 cm^3 hermetic reciprocating compressor. It has been partially modified, in such a way that do not alter the original operation of the system, by adding different transparent sections as well as an extra section that allows testing several positions of filters and capillary tubes (Figure 1). The frame heater, originally placed at the condenser outlet, has been moved to the compressor discharge in order to be able to study just the condenser outlet and the filter inlet conditions.

The original expansion device, a capillary tube with liquid-to-suction heat exchanger (CT-LSHX), has been replaced by an experimental facility made up of three capillary tubes, of same geometry as the original one, wrapped up around the suction line. Each capillary tube has a total length equal to 2.44 m, internal diameter of 0.6 mm and is connected to a different transparent filter (Figure 2). A net of tubes and valves allows selecting the operating capillary tube and filter. The three filters are positioned differently in order to investigate the effect of their orientation on the flow pattern at the condenser outlet and at the capillary tube inlet; two of them are in vertical position, but with opposite flow direction, while the third one is horizontally oriented. Finally, the length of the capillary tube within the filter can be also varied.

The visualization of the refrigerant flow at the condenser outlet is possible by using a transparent section which replaces the final length of the original condenser (Figure 1). The transparent pipe is made of Perfluoralkoxy (PFA), has a total length of 1.3 m and an internal diameter equal to the original one (3.5 mm).

The temperatures are monitored by a set of thermocouples (type T) located along the refrigerant circuit (Figure 3) and inside both the fresh food cabinet (FF) and the freezer cabinet (FZ). The pressure is measured by means of two pressure transducers (P1 and P2) positioned at the condenser outlet and in the suction line which have an uncertainty lower than ≈ ± 1% full sensor scale.

The experimental apparatus is placed in a climatic chamber and equipped with a system for data acquisition and processing.

2.2 Experimental Campaign

The experimental tests are focused on the visualization of the refrigerant flow at the condenser outlet and at the capillary tube inlet in order to conclude about the real state of the refrigerant at the condenser outlet. Nine different configurations have been tested (Table 1) involving three filter orientations, and for each filter, three positions of the capillary tube within the filter. The total capillary tube length was always kept constant.

A preliminary optimization study established the optimal refrigerant charge at 62 grams. The environmental conditions in the climatic chamber have been maintained at a temperature of 25 °C.

During the tests, the refrigerator is controlled by its electronics, alternating two different operating modes, freezer mode (FZ) and dual mode (FF+FZ). The FF+FZ mode is when air from evaporator is supplied to both fresh food cabinet (FF) and the freezer cabinet (FZ), while the FZ (Freezer mode) is when air from air evaporator is only supplied to the freezer since the fresh food cabinet is already within the setting range of temperature. Once the freezer achieves the lowest temperature, the compressor switches off. The cycle starts again when the air inside the cabinets warms up due to the heat load.

3. RESULTS AND DISCUSSION

3.1 Temperature profiles

The condenser temperature profile is analyzed in Figure 4 for the optimal charge of refrigerant. In both operating modes the saturation temperature (evaluated with the outlet condenser pressure) is always slightly higher than the temperature measured by the thermocouples on the wall where condensation is expected to be present. Despite the thermocouple is highly insulated from ambient, this difference can be explained by a certain longitudinal heat conduction and uncertainty of measurements. In Figure 4, the temperature value practically does not change from T1 to T5, what can be understood as the condenser area where the two-phase flow is present. The temperature measured by the thermocouples T6 to T8 decreases from the value at T5, what allows thinking that a certain subcooling exists. In order to study the effect of the refrigerant charge on the condenser temperature profile a set of tests with different refrigerant charges was carried out. Figure 5 depicts the case with the largest refrigerant charge (73 g). In this case, the analysis of the condenser temperature profile indicates that the subcooling starts at temperature T4, earlier than in the optimal charge case. The temperature difference between T5, T6 and T7 are becoming more important until reaching T8, where the temperature seems to stop decreasing. This fact can be explained by the fact that we almost reach the temperature of the climatic chamber thus no more heat can be exchanged. As expected, the temperature condensation and subcooling are higher than in the optimal charge case. Figure 6 shows the evolution of the subcooling when increasing the refrigerant charge. The reported subcooling is defined as the difference between saturated temperature minus the value of T8 in the last moment previous the compressor shuts down. The non-linear trend of the subcooling could be explained with the uncertainty of the temperature measurements.

3.2 Visualization of the flow pattern at the condenser outlet

In Figure 7 and Figure 8 are reported two pictures of the transparent section built in the tube-and-wire condenser when refrigerator was running with optimal refrigerant charge, which minimized the energy consumption. The two figures show clearly the presence of two-phase flow at the condenser outlet due to the presence of both liquid and bubbles of vapor. The visualization did not show noticeable differences between both operating modes of the refrigerator, FF+FZ and FZ. The images were taken when transient phenomena due to the start-up of compressor had finished and quasi-steady state conditions were established.

The situation analyzed corresponds to a really low mass velocity G, which is about 18 kg/m^2s in FF+FZ. For the tested conditions, the flow pattern correlation of Thome *et al.* (2003) predicts a stratified regime. By observation of Figures 7 and 8, this flow regime can also be characterized as stratified regime where the liquid fills the bottom of the tube while the vapor is present only at the upper part. In addition, an intermittent flow appears when in some sections the liquid phase occupies the full cross section due to some minor liquid waves or just because of surface tension given the small diameter (3.5 mm).

It was observed that the U-bends separate the two phases: the liquid is pushed by the centrifugal forces towards the external part of the curve and, at the same time, the vapor occupies the internal part. At the outlet of these U-bends, the flow becomes more stratified as shown in Figure 8. The global overview is that elongated bubbles go through the condenser until reach the filter and the capillary tube inlet. The same flow patterns were observed for all the tested refrigerant charges, including the highest case of 73 grams.

Opposite to the conclusions made from the temperature field analysis, with these visualizations we could conclude that there is no subcooled liquid. Boeng and Melo (2012) visualized this situation at the capillary tube inlet and they explained thisfact as a non-equilibrium mixture of subcooled liquid and saturated vapor. However, in this study, the transparent section is quite long and it can even be considered as adiabatic compared with a normal tube, so it could have enough length to achieve equilibrium state or at least showing some evolution towards the equilibrium. Nevertheless, no evolution was shown to this end. On the other hand, further experimental studies are required to characterize the actual condenser outlet conditions.

In order to analyze if these conclusions are affected by the refrigerant charge, the same visualizations were performed with a charge increase of 15 grams, which is a pretty large charge for these systems. The visualizations were basically the same.

3.3 Visualization of the refrigerant flow at the capillary tube inlet

Figures 9, 10 and 11 depict the flow conditions at capillary tube inlet for all the arrangements shown in Table 1. Same as occurred for the outlet condenser visualization, the images did not show noticeable differences between both operating modes, FF+FZ (Dual mode) and FZ (freezer mode). Also in this case, the images were taken when the quasi-steady state conditions were established.

Figure 9 shows the different flow condition at the capillary tube inlet during the tests 1-3 of Table 1, which are characterized by having the capillary tube inlet at the bottom of the filter and the refrigerant flowing downwards. The liquid fills the bottom of the filter until reaching the level defined by the section where the capillary tube inlet is. The flow at this section was quite unstable showing fast and short oscillations (1 millimeter approximately) due to the droplets falling down from the filter. Most of the time, the flow condition corresponded to the one depicted in the Figure 9, where can be observed that, once the liquid reaches the capillary tube inlet, a small vortex appears. This phenomenon highlights that the capillary tube draws in both liquid and vapor.

In order to demonstrate that the filter is not working as a liquid accumulator, the position of the capillary within the filter was varied (Tests 2 and 3) respect to the Test 1. By observing the figures, it is evident that the liquid level always follows the capillary tube inlet. Figure 9 shows clearly that regardless its position, the capillary tube draws in always refrigerant with a certain amount of vapor. In fact, the filter contains always a constant amount of vapor and liquid that comes from the filter walls and from the liquid droplets. This amount depends on the position of the capillary tube within the filter.

Figure 10 shows the corresponding tests for the filter mounted in the opposite direction; the refrigerant comes from the bottom and flows up until reaching the capillary tube inlet. In the pictures can be seen bubbles of vapor flowing through the liquid and reaching the upper part of the filter. Now, stronger oscillations than in the previous case were present at the interface because of the abrupt interruption of the bubbles, which flow towards the capillary inlet. In this case, the interface is quite irregular and the capillary tube draws in alternately both liquid and vapor. As in the previous case, the liquid level follows the displacement of capillary tube inlet (Tests 5 and 6). Test 4 shows a situation that can be quite confusing if the capillary tube inlet is not visible since it could suggest that is fully filled of liquid when it is not true; it will always exist a certain volume with vapor above the capillary tube inlet.

Figure 11 reports the pictures of the filter horizontally oriented. In these operating conditions, only a very small vortex appears at the capillary tube inlet. No significant change occurs when the capillary tube inlet is moved along the filter. Now, the interface liquid-vapor can be considered practically motionless in all the cases. This fact is very important because we can assure that the capillary tube inlet is drawing in constantly a certain amount of vapor in steady conditions. This observation was not so clear in Figures 9 and 10 because the gravity was affecting of the vapor-liquid interface trough the action of either the bubbles or droplets.

The visualization of Figures 9, 10 and 11 confirms the presence of two-phase flow at the capillary tube inlet, confirming that the filter is not operating as a liquid receiver. Therefore, if we assume thermodynamic equilibrium between both phases, the condensation cannot be considered as completed in the condenser. The unbalanced matching between compressor and capillary tube could be one of the reasons for such observations, i.e. the system would be equipped with a capillary tube with an expansion capacity very large compared with the compressor needs. This situation would lead the system to work in an operating point less efficient compared to a system working with an effective subcooling.

The same visualizations were performed with a charge increase of 15 grams.

The visualization work cannot demonstrate by itself that the refrigerant has not fully condensate in the condenser, but it only shows that there are two phases. A non-equilibrium condition could explain these observations. In the author's opinion, the system should be equipped with a more restrictive expansion device able to provide a much lower expansion capacity in order to have liquid at the capillary tube inlet.

Another possible solution would be the design of the filter so that it works as a liquid receiver. This design would lead the system to work always with saturated conditions at the condenser outlet with the only disadvantage of not allowing the identification of the optimum refrigerant charge. On the other hand, given the small volumes of these components and the importance of the transient process in this type of system, this task looks quite difficult.

4. CONCLUSIONS

An experimental work aimed to visualize the refrigerant flow at the condenser outlet and at the capillary tube inlet has been presented. In order to deepen the studies about the actual refrigerant conditions in the condenser outlet of these refrigeration systems, a novel experimental test bench has been designed and mounted on a high efficiency household refrigerator. The main results can be summarized as follow:

- The analysis of the temperature profile shows the presence of subcooled liquid at the condenser outlet, increasing its value as the refrigerant charge is increased.
- The visualization of the condenser outlet shows clearly the presence of two-phase flow regardless the refrigerant charge. The dominant flow regime looks to be stratified, while in some sector intermittent flow appears.
- Regardless the orientation of the filter, the capillary tube position inside it and the refrigerant charge, the capillary is always drawing in a mixture of liquid and vapor. In all the tested filters, the liquid level follows the capillary entrance demonstrating that filter is not operating as a liquid receiver.
- The visualizations did not change qualitatively even with a charge increase of 15 grams.

The visualization work cannot demonstrate by itself that the refrigerant has not fully condensate in the condenser, but it only shows that there are two phases. A non-equilibrium condition could explain this observation. In the author’s opinion the compressor would need a more restrictive capillary tube, but further woks are required to confirm this idea.

ACKNOWLEDGEMENTS

The work of Laetitia Bardoulet in this project was partially supported by Santiago Grisolía 2015 program which is funded by the Generalitat Valenciana with reference number GRISOLIA/2015/021.

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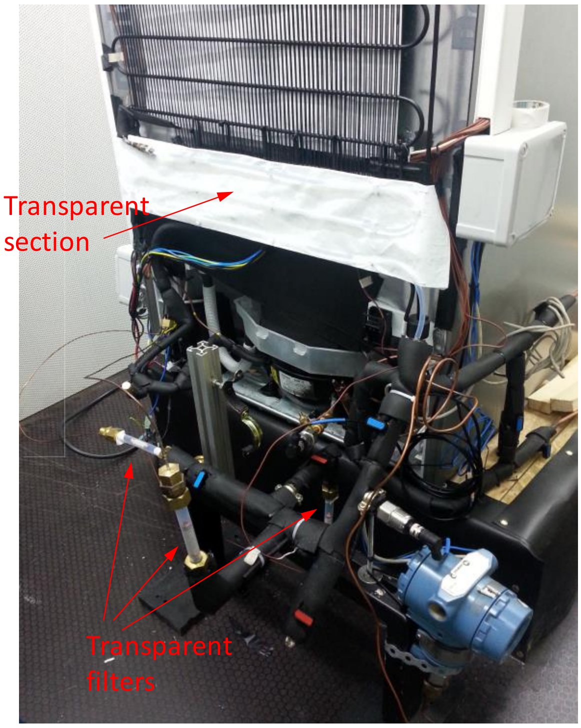


Figure 1: Test bench

Figure 2: Transparent filter

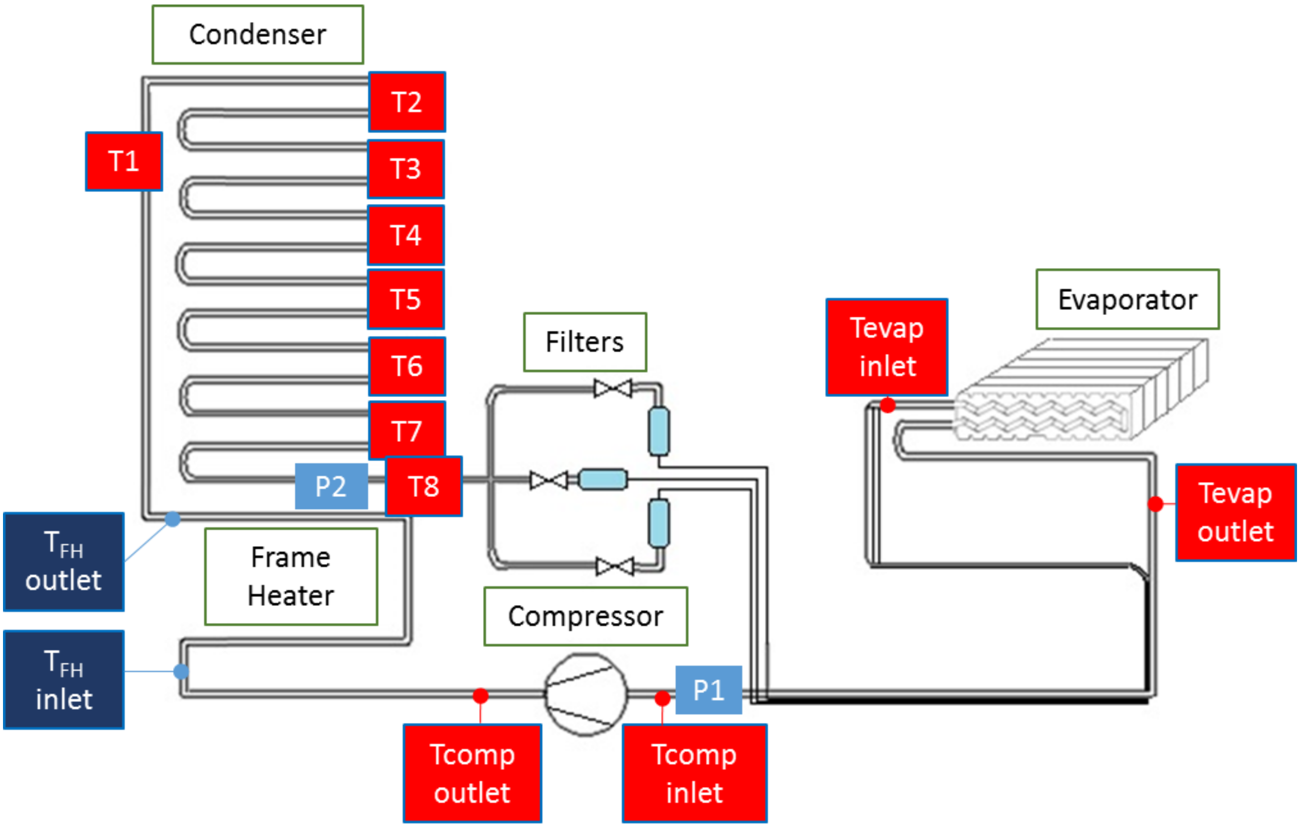


Figure 3: Position of pressure and temperature measurements

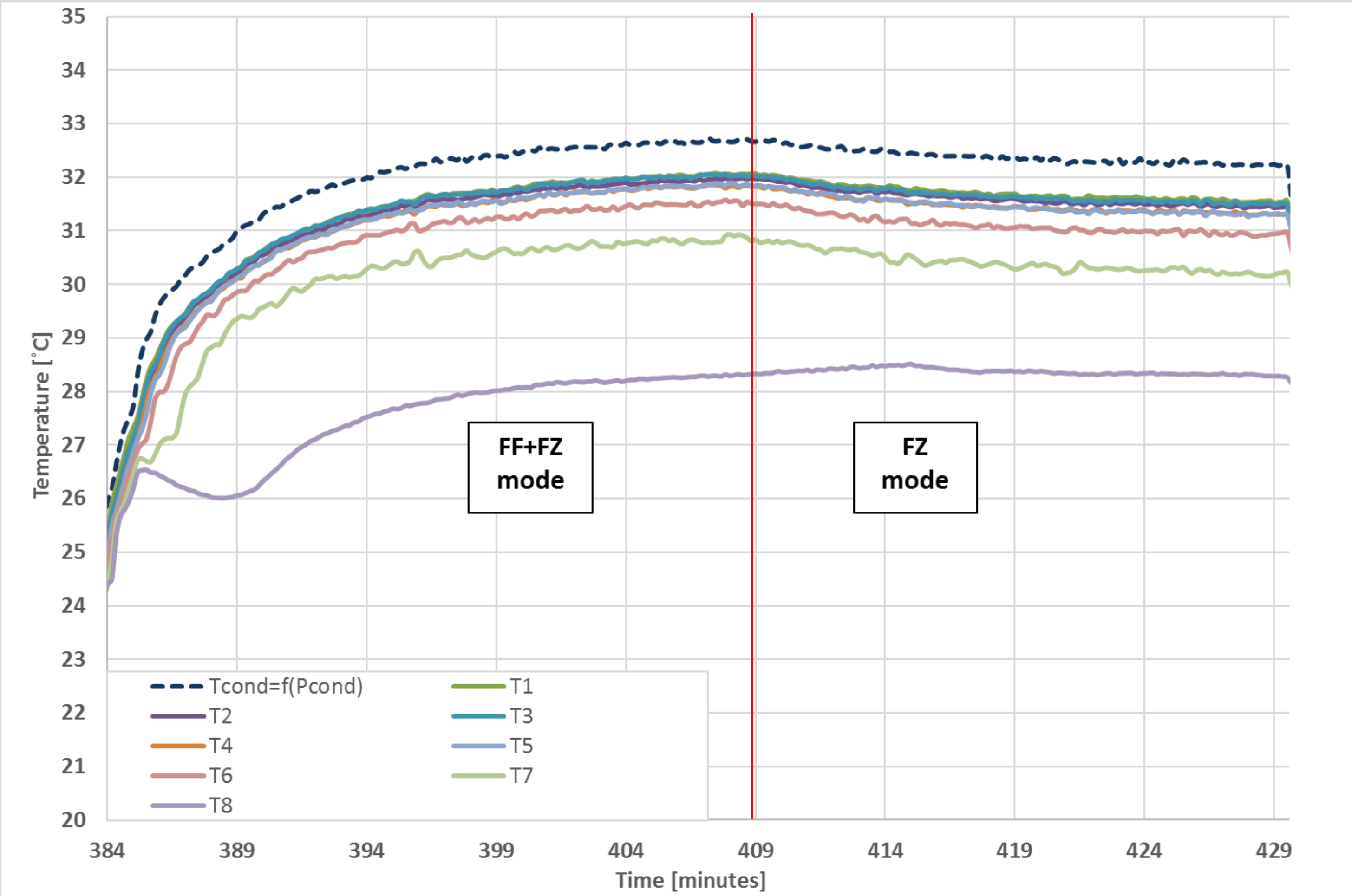


Figure 4: Condenser temperature profile for optimal refrigerant charge

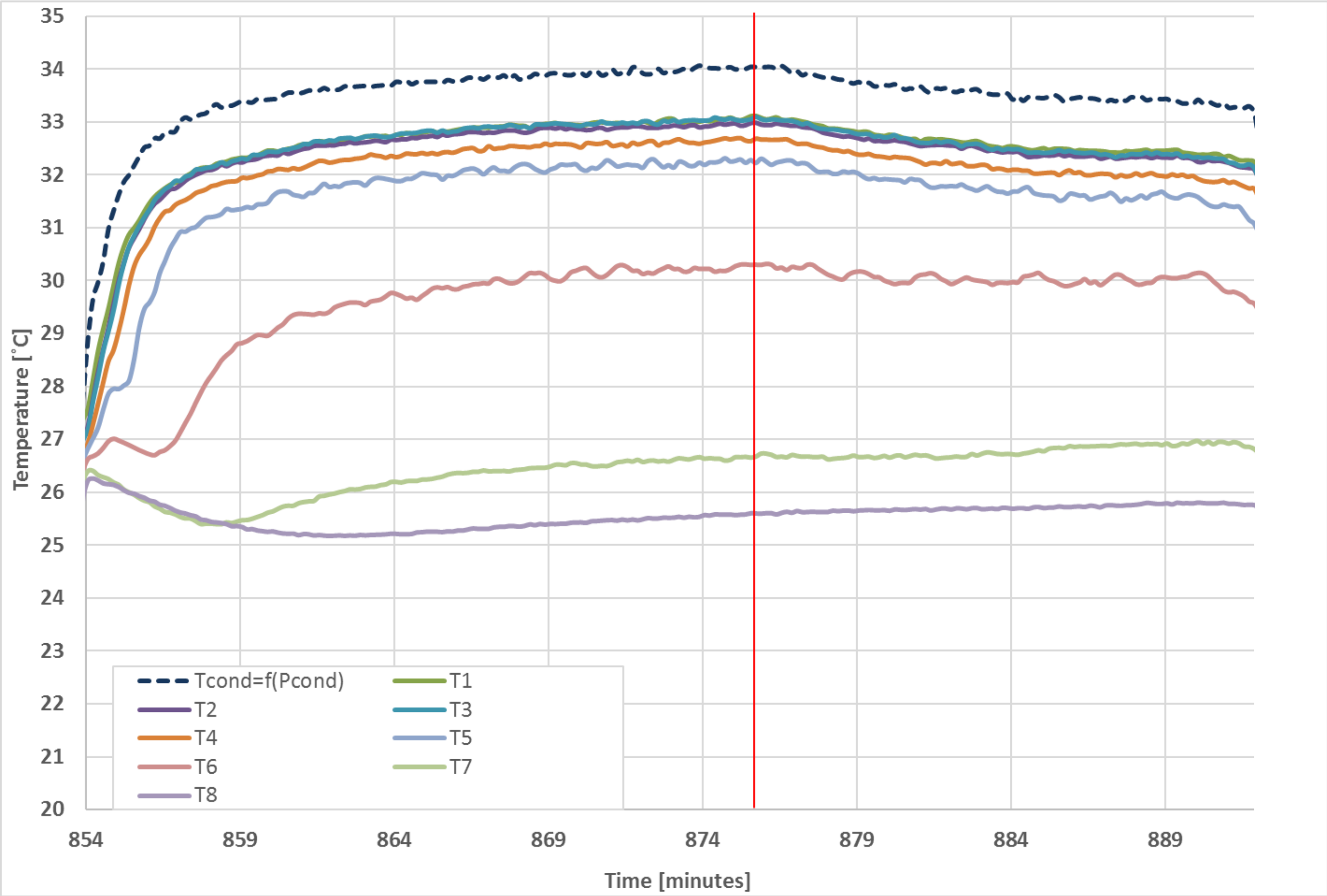


Figure 5: Condenser temperature profile for the highest refrigerant charge

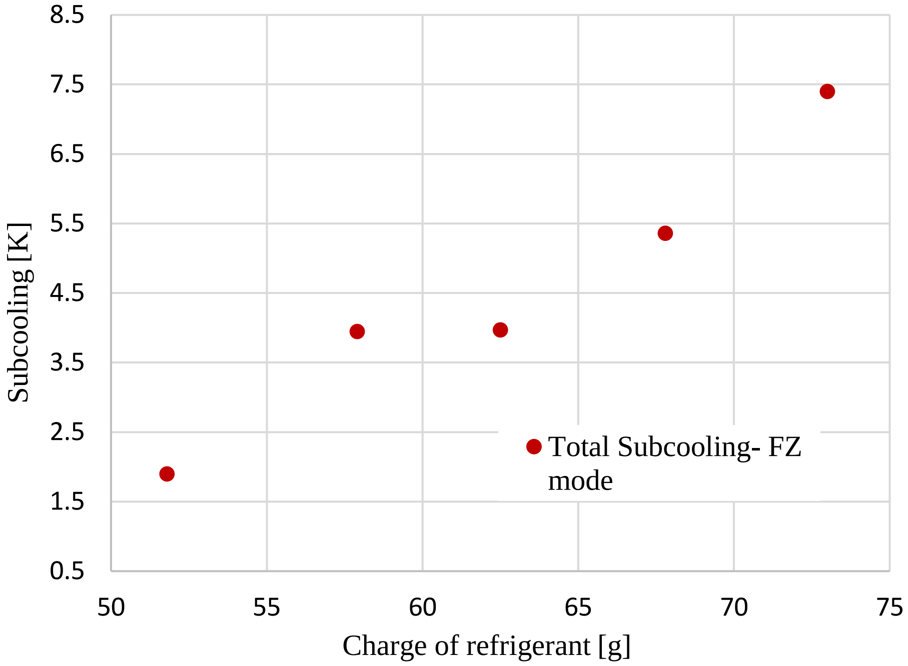


Figure 6: Evolution of the subcooling as a function of refrigerant charge

Figure 7: Refrigerant flow at the condenser bends

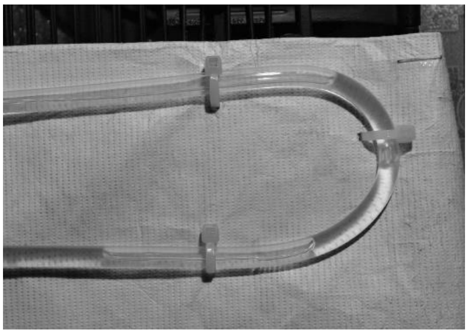
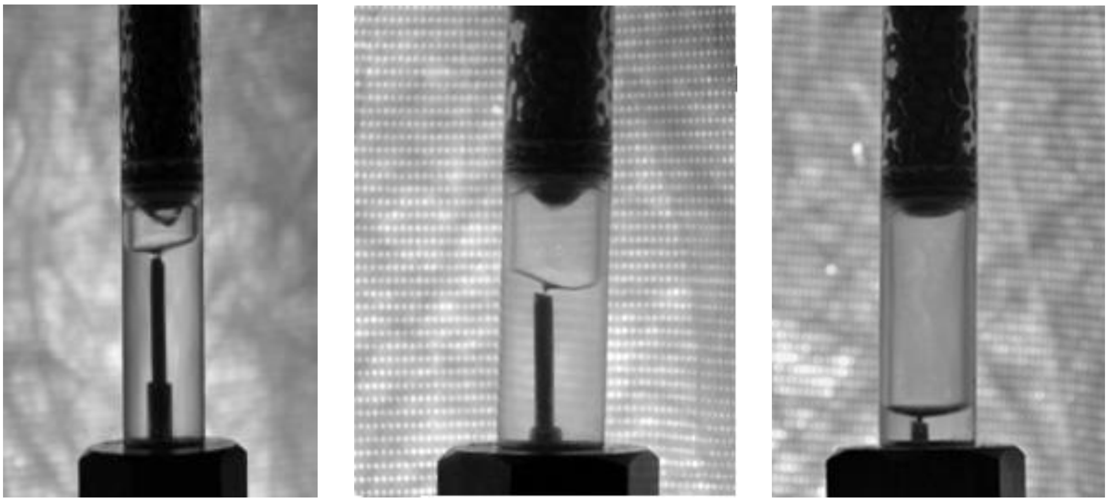
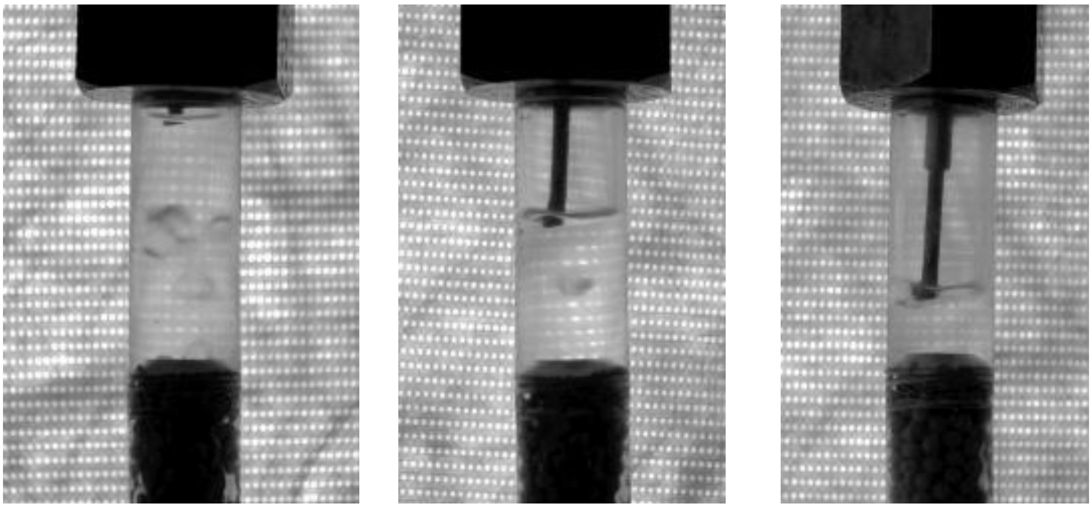


Figure 8: Refrigerant flow in the last part of the condenser



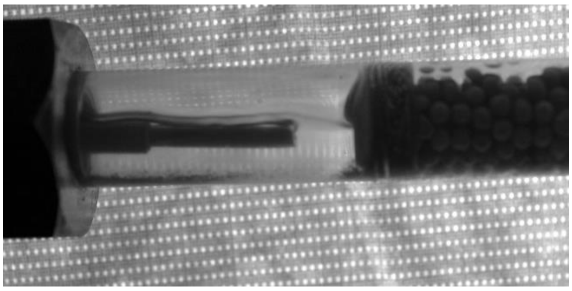
Test 1 **Test 2** **Test 3**

Figure 9: Refrigerant flow at the capillary tube inlet during the test 1,2 and 3

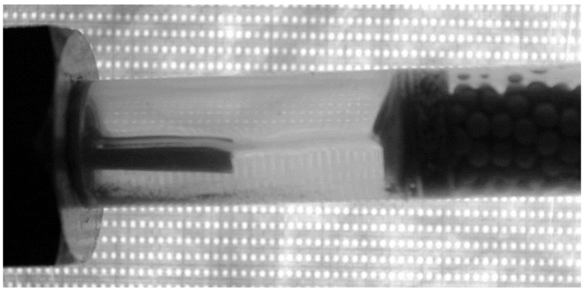


Test 4 **Test 5** **Test 6**

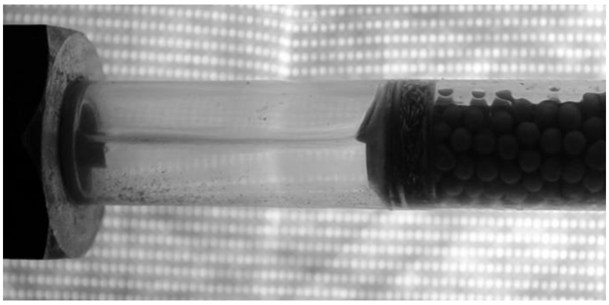
Figure 10: Refrigerant flow at the capillary tube inlet during the test 4, 5 and 6



Test 7



Test 8



Test 9

Figure 11: Refrigerant flow at the capillary tube inlet during the test 7, 8 and 9

Filter orientation	**Flow direction**	**Capillary tube position inside the filter**	**Nº**
Vertical	Downwards	Top	1
		Middle	2
		Low	3
Vertical	Upwards	Top	4
		Middle	5
		Low	6
Horizontal	Horizontal	Top	7
		Middle	8
		Low	9

Table 1: Tests matrix