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An Experimental Study on Capillary Tube Flow and its Effect on the Acoustic Behavior of Household Refrigerators

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ABSTRACT

The aim of this work was to study the relationship between capillary tube flow and the acoustic behavior of household refrigerators by investigating a particular type of fluid-induced noise, known as fluctuating noise. To this end a household refrigerator was carefully instrumented and firstly tested in a reverberant chamber and secondly in a climate-controlled chamber. Acceleration measurements were taken at the evaporator inlet pipe showing that the refrigerant flow in that region was highly pulsating. Visualization of the flow pattern at the inlet of the capillary tube was also carried out and revealed the presence of vapor bubbles for most of the time. A needle valve was then installed in series with the freezer capillary tube in order to increase the restriction and match the compressor and the capillary tube mass flow rates. The restriction provided by the optimum needle valve-capillary tube pair was then converted into an equivalent capillary tube. It was found that the higher-restriction capillary tube attenuated the pulsating characteristic of the refrigerant flow, almost completely attenuating the disturbing fluctuating noise.

1. INTRODUCTION

Over the years a considerable amount of research effort has been aimed at increasing the energy efficiency of industrialized products in general. In addition, the acoustic aspect has always been a source of concern among manufacturers of any mechanical device. A highly efficient product will not be of commercial interest if it makes a lot of noise (Kunio and Marroquin, 2006). By definition, sound becomes noise whenever it is uncomfortable and undesirable.

When it comes to acoustical behavior, the household sector is a field of particular interest. The undesirability of noise is even greater in an environment which is intended to be a place for rest and leisure. For the household refrigeration industry, which makes a product that works 24 h per day, noise emissions constitute an increasing high importance factor. The compressor has been the most critical component since the early days of vapor compression refrigeration systems. Substantial research has been carried out to turn the compressor into a more reliable and silent component, highlighting other sources of noise, such as that generated by the refrigerant flow through the capillary tube, the so-called expansion noise. The sound waves transmit vibrational energy to the structure of the refrigerator, exciting it and generating audible sound, mostly characterized as noise.

This paper describes a study on fluctuating noise – one of the several types of expansion noise – focused on the effects of the flow pattern at the entrance of the capillary tube on the acoustical behavior of household refrigerators. Herein lays an important consideration: the noise that is heard outside the appliance by a customer or captured by a microphone in an appropriate acoustic test room is a result of the interactions between the noise source (intermittent flow pattern in the evaporator), the energy transmission paths (physical connections, insulating material) and the radiators (evaporator, cabinet walls). Generally, the noise source in most refrigerators is similar to that investigated in this study, but since the structural aspects vary among refrigerator models, the transmission paths and the radiators may behave differently. Thus, even though the evaporator vibrates strongly, the noise may not be noticeable outside the appliance.

1.1 Literature Review

It is well known that throttling valves and other flow control devices are a significant source of noise in industrial environments (Reethoff, 1978). There are a great number of studies dealing with the generation of noise in expansion devices of air and steam systems (Baumann, 1984, 1987; Reethoff, 1978; Reethoff and Ward, 1986). In refrigeration systems, however, the expansion noise is a relatively new field of study.

Early studies dealt with designing a special junction to be placed between the capillary tube and the evaporator in order to reduce the abrupt expansion from one component to another (Drury and Priest, 1970; Wattley and Dankel, 1988). Kubo *et al.* (1983) studied the noise generated by turbulent jets. A silencer was designed, constructed and installed, attenuating the high frequency noise caused by the turbulent jet at the exit of the capillary tube. Singh *et al.* (1999) published an omnibus study on expansion noise in refrigeration systems. Different expansion devices (capillary tubes, orifice tubes, thermostatic and electronic expansion valves) were tested in a specifically designed refrigeration loop. The authors concluded that the sound pressure generated by the fluid flow through capillary tubes is a direct function of the mass flow rate, of the pressure difference to which the expansion device is submitted and of the refrigerant quality at the capillary outlet.

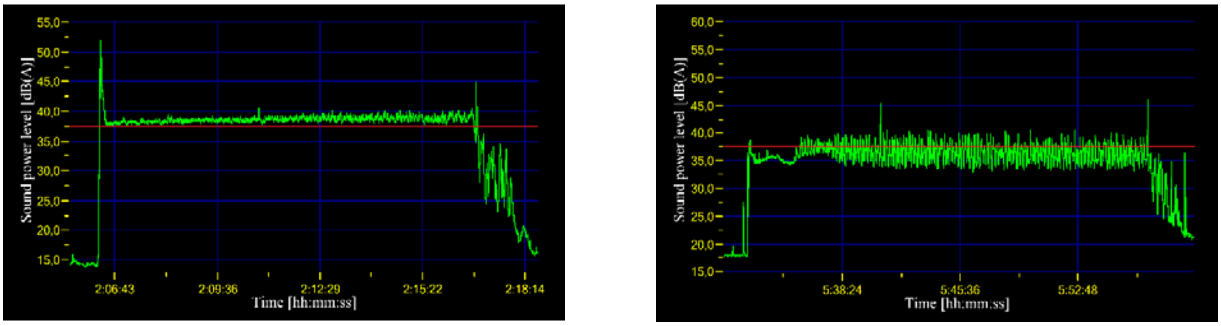
McLevige and Miller (2001) studied an anomalous acoustic phenomenon, known as popping noise, a burst that is heard soon after the compressor start-up. They concluded that vapor bubbles enter the capillary tube, lose heat to the cold suction line at a high rate and collapse, creating what is known as condensation induced shock (CIS). Hartmann and Melo (2013) also studied the popping noise phenomenon and concluded that the liquid level inside the filter dryer should be increased during the start-up period. To this end an additional internal heat exchanger was installed between the liquid and the suction line, averting the noise without compromising the system performance. Han *et al.* (2009, 2010) carried out analytical and experimental studies aiming to identify the fundamental causes of fluid-induced noise in household refrigerators. Han *et al.* (2011) subsequently performed more in-depth studies to better understand the noise generated by bubbles flowing in a tube.

The literature review highlighted that the expansion device is the main source of fluid-induced noise in household refrigerators. There are basically two sets of physical phenomena related to the sound generated by capillary tubes. The first relates to the expansion process itself, involving flow acceleration and partial fluid vaporization, which will always be present in household refrigerators. The second relates to the fluid flow pattern at the entrance of the expansion device, which depends on the system design.

1.2 Fluctuating Noise

Figure 1a shows the overall sound power level during the freezer cycle of a typical dual-evaporator household refrigerator equipped with a capillary tube and a variable speed compressor running with R-600a. Figure 1b, on the other hand, shows the overall sound power level of a similar, but sick – with anomalous noise – refrigerator. Both tests were carried out in a reverberant chamber and followed standardized procedures. It is worth noting that the average sound power level of both refrigerators is approximately the same, but the fluctuations around 3 min after compressor start-up are much more intense in Figure 1b, meaning that the fluid-induced noise started to play an important role in the sick refrigerator.

For most standards in effect around the globe the sound power level shown in Figure 1b is still lower than the acceptable limits. For the typical customer, however, this acoustic behavior is unpleasant, since the sound intensity varies greatly within a short period of time (± 2.5 dBA in 4 seconds) and continues to vary during the entire compressor on time. Moreover, each one of the many sound power cycles shown in Figure 1b resembles the noise caused by using a straw to suck soda out of a practically empty can.



(a) (b)

Figure 1: Sound power level of a (a) normal and (b) sick refrigerator.

2. THERMODYNAMIC CHARACTERIZATION OF NOISE

A dual-evaporator, bottom-mount refrigerator equipped with a variable speed compressor was the subject of this study. It is essentially a typical by-pass two-circuit cycle (Yoon *et al.*, 2013), with two operating modes. In the first, named the fresh-food (FF) mode, the refrigerant flow is routed to the FF capillary, activating the FF roll-bond evaporator and cooling down the fresh-food compartment. The refrigerant leaving the FF roll-bond evaporator travels to the freezer (FZ) wrap-around evaporator. In the second mode, named the FZ mode, only the FZ evaporator is activated, dropping the temperature of the freezer compartment.

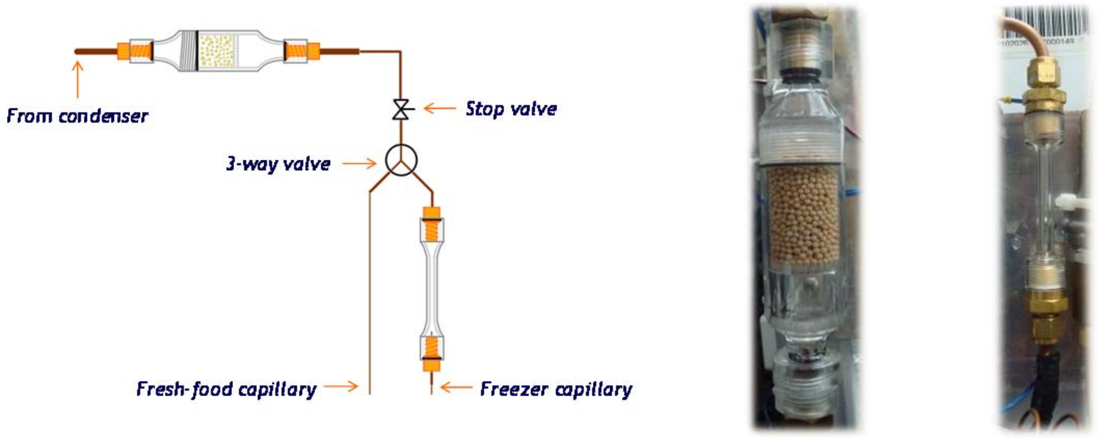
A total of 33 T-type thermocouples were installed along the refrigeration loop, as well as in the refrigerated compartments. Five absolute pressure transducers were installed at the compressor suction and discharge and at the inlet of the evaporators and of the filter dryer.

Experimental evidence collected by Han *et al.* (2009) support the hypothesis that fluid-induced noise only occurs in two-phase flow regions. The refrigerant flow through the heat exchangers of the appliance under study is not complex enough to cause fluid-induced noise since the design of these components is rather simple. On the contrary, the evaporator inlet pipe receives a high speed, two-phase turbulent jet from the capillary tube, creating a chaotic environment in which vapor bubbles oscillate, coalesce and collapse. Therefore, this region tends to have the highest fluid-induced noise generation, via vibrations caused by random flow patterns, which excite the evaporator and/or the refrigerator structure. An accelerometer was thus installed at the FZ evaporator inlet pipe using a thin layer of cyanoacrylate, in order to capture possible flow oscillations.

Hartmann and Melo (2013) constructed a sight glass to observe the flow pattern at the inlet of the capillary tube. They noted that even with a subcooling of the order of 5 K some vapor bubbles were still present in the refrigerant flow. To better and more safely visualize the refrigerant flow without affecting the original volume of the refrigerator, an acrylic filter dryer was built to replace the original copper dryer, as shown in Figures 2a and 2b. Since the FZ capillary tube is positioned after the 3-way valve, an acrylic sight glass was also built and installed at the FZ capillary inlet, as shown in Figure 2c.

According to the manufacturer's recommendation the current analyses were carried in steady-state conditions, in the FZ mode and with the compressor running at its lowest speed, as shown in Figure 3, that is, the same conditions under which the microphone readings shown in Figure 1b were obtained. Furthermore, all tests were performed under the ambient conditions of 25 °C / 50%.

The baseline acceleration profile for the evaporator inlet pipe is shown in Figure 4. It is worth noting that there is a clear correlation between the acceleration readings in Figure 4 and the sound power measurements shown in Figure 1b. It can also be noted that there is an almost cyclical oscillation of the evaporator inlet pipe acceleration. Using a simple computer code written in MatLab® it was possible to convert the acceleration readings into a sound file, to obtain a qualitative perspective of the tube vibrations.



(a) (b) (c)

Figure 2: Arrangement (a) of the acrylic filter dryer (b) and the acrylic sight glass at the FZ capillary inlet (c).

When the acceleration oscillates strongly, as seen at around t = 4 s in Figure 4, there is an increase in the sound level of the audible file generated by the computer code, and the typical sucking-soda-out-of-an-empty-can noise can be heard. When the acceleration oscillates smoothly, the sound file reveals a low intensity noise, reminiscent of a soft breeze. This cyclical pattern has an average period of around 4 s.

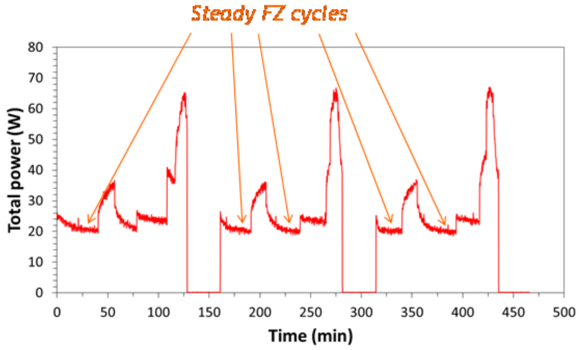


Figure 3: Criterion for the accelerometer readings.

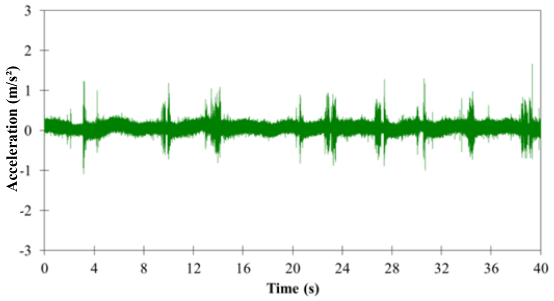
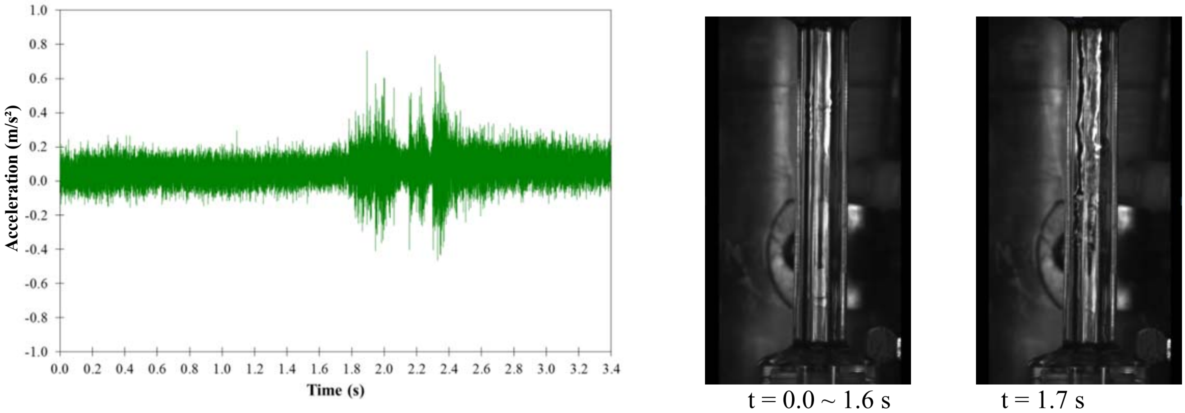


Figure 4: Accelerometer readings: baseline system.

A high speed video camera was used to record the refrigerant flow at the FZ capillary inlet. The camera and the accelerometer were triggered at the same time, in order to investigate whether or not the evaporator inlet pipe vibrations, shown in Figure 5a, are related to the refrigerant flow pattern at the entrance of the capillary tube (Figure 5b). The video camera was set to a recording rate of 200 frames per second and the accelerometer data to an acquisition rate of 25,600 readings per second.

During the first 1.6 s there is an annular refrigerant flow at the capillary inlet, with the refrigerant vapor flowing through the center of the acrylic sight glass and a thin layer of liquid refrigerant almost adhered to its inner wall. At around 1.7 s a liquid slug is pushed into the capillary, causing the acceleration readings to oscillate dramatically just 0.1 s later. This strongly agitated slug flow pattern at the entrance of the capillary is repeated at t = 1.9 s, t = 2.1 s and t = 2.3 s, all of these events being noted both through the acrylic sight glass and in the acceleration readings.

Since there is intermittence in the refrigerant flow at the capillary inlet, the refrigerant flush at the capillary outlet is highly pulsating. The evaporator inlet pipe is horizontal, which leads to a stratified flow with liquid settling in the lower portion of the tube and vapor occupying the upper section, as shown in Figure 6a. From time to time, the violent flush that comes out of the capillary encounters this interface and produces a tremendous degree of agitation in the refrigerant flow, causing the evaporator to vibrate, as illustrated in Figure 6b. According to the acceleration and microphone measurements, this vibration has enough energy to generate audible noise outside the refrigerator.



t = 0.0 ~ 1.6 s t = 1.7 s

(b)

(a)

Figure 5: High speed accelerometer readings (a) and flow pattern at the FZ capillary inlet (b): baseline system.

(a) (b)

Figure 6: Illustration of the flow pattern at the evaporator inlet as a consequence of vapor (a) and slug (b) flow at the entrance of the capillary.

In order for a refrigerator to operate in steady state the mass flow displaced by the compressor must equal the mass flow through the capillary tube. Despite being macroscopically detectable by the data acquisition system, it was found that the appliance under study does not operate in a true steady state, due to the cyclic flow pattern at the capillary inlet. To support this statement, the compressor and capillary mass flow rates were plotted on the same chart as a function of the pressure ratio (Figure 7).

The compressor curves were obtained through the volumetric efficiency map, derived from catalog data, and the capillary curve was estimated using the model proposed by Hermes *et al.* (2010), inputting geometric data provided by the refrigerator manufacturer and measured operating conditions. It can be clearly noted that the measured operation point, at 1300 RPM, is a long way from the theoretical steady-state operating point, showing that the capillary tube is oversized for this appliance.

It was found that there are slugs of liquid flowing into the capillary tube, followed by pockets of refrigerant vapor. The instant t = 0 s in Figures 5a and 5b marks the beginning of a new cycle in the intermittent flow pattern at the capillary inlet, when the pocket of vapor has just started to flow into it. At this first stage the pressure ratio is high and so is the capillary mass flow rate. The mass contained in the pocket of vapor thus flows rapidly to the evaporator, dropping the pressure at the inlet of the capillary tube. In the second stage the pressure ratio is much lower and so is the capillary mass flow rate. The reduced pressure at the capillary inlet forces the small amount of liquid formed in the condenser to flow rapidly into the capillary, not allowing time for a stable liquid supply to be created.

Based on these observations it can be concluded that the fluctuating noise phenomenon is caused by the transient operation of the capillary tube, regardless of the compressor steady-state regime. Such unconformity originates from the oversizing of the capillary tube, allowing refrigerant to flow into it at a rate higher than that which the compressor can displace.

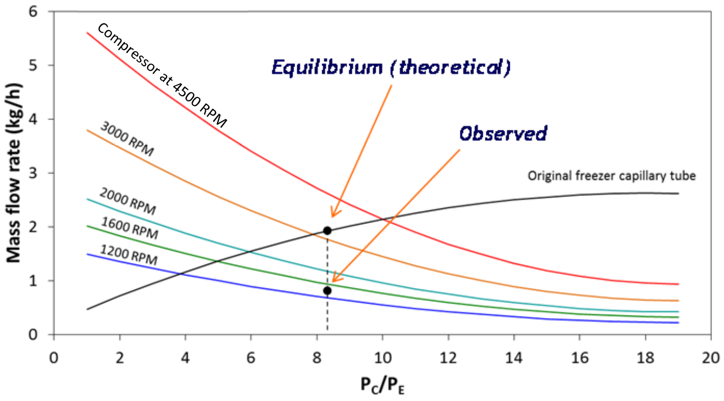


Figure 7: Compressor and original FZ capillary mass flow rates, as a function of the pressure ratio.

3. ACOUSTICAL EFFECTS OF THE FLOW PATTERN AT THE CAPILLARY INLET

The flow pattern at the capillary inlet strongly affects the dynamic behavior of the evaporator, as shown in the previous section. It can be stated that the more oscillating the flow pattern is the stronger the accelerations of the evaporator will be. It can then be concluded that in order to attenuate the fluctuating noise a steady, single phase flow at the capillary inlet is needed, preferably a constant liquid flow so as not to affect the thermodynamic performance of the refrigerator. On observing Figure 7, three approaches are revealed:

i) *Increasing the compressor speed*. If the baseline operating conditions could be maintained constant, a true steady-state regime would be achieved at the compressor speed of 3200 RPM. But the pressure ratio increases when the compressor speed is increased, shifting the pressure ratio to the right. After several tests it was concluded that a rise in the compressor speed will never provide a constant liquid flow at the capillary inlet.
ii) *Increasing the refrigerant charge*. The pressure ratio can be decreased by increasing the mass of refrigerant contained in the refrigeration loop, approximating the compressor and capillary mass flow rates. Another set of experiments was carried out and, after more than doubling the refrigerant charge, no considerable effect was obtained.
iii) *Increasing the capillary tube restriction*. As shown in Figure 8, a more restrictive capillary tube could be designed, in such a way that the mass flow rate is equal to or lower than the mass flow displaced by the compressor.

To verify the effects of the increased expansion device restriction in a simple, economic and fast manner, a micrometric needle valve was installed immediately before the acrylic sight glass, as shown in Figure 9. This particular needle valve has an orifice of 1.42 mm and 9 full turns between completely opened and completely closed positions, with a scale interval of 0.04 turns. The aim was to gradually close the needle valve, while monitoring the flow pattern at the capillary inlet, until the evaporator acceleration profile ceased to show the characteristic noise patterns.

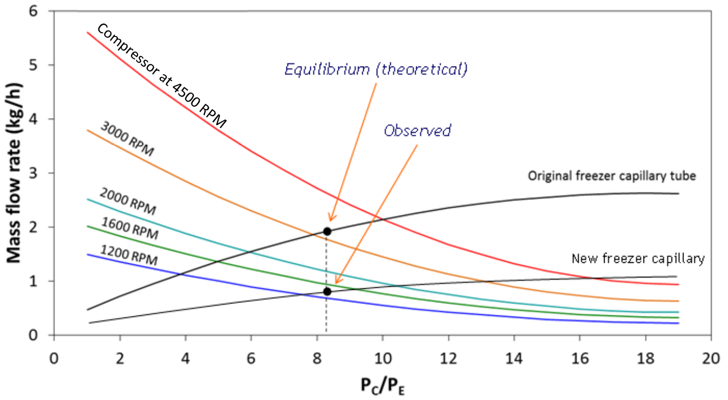


Figure 8: Compressor and proposed FZ capillary mass flow rates, as a function of the pressure ratio.

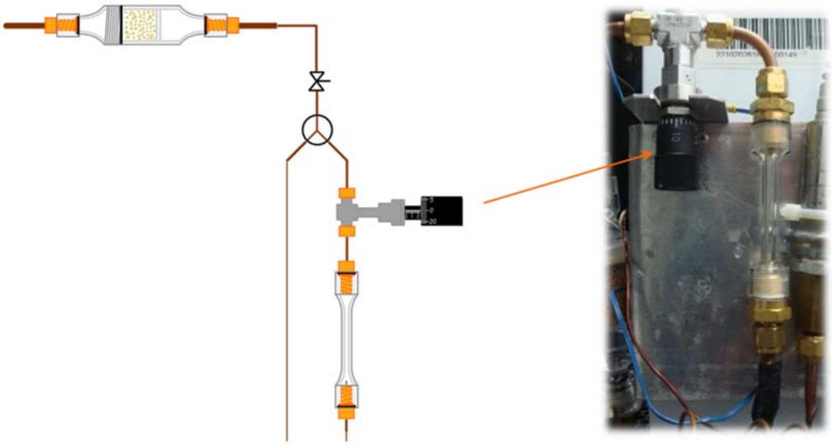
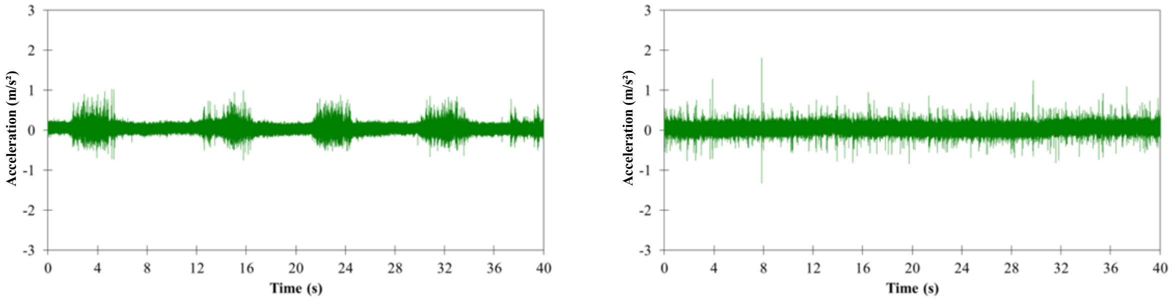


Figure 9: Needle valve installed before the FZ capillary tube.

Figure 10 shows the evaporator acceleration profiles for two needle valve openings (VOs). A VO of 100% indicates that the needle valve is fully opened and at VO = 0% the needle valve is fully closed. As the needle valve is closed the fluid flow becomes less intermittent, with progressively smaller pockets of vapor coming from the condenser, passing through the valve and entering the capillary. For this reason, the time interval between two consecutive strong oscillations in the evaporator acceleration becomes progressively smaller. At VO = 3% this time interval is no longer discernible. However, there are intense acceleration spikes throughout the FZ cycle.

Figure 11a shows a zoom of the accelerometer readings for VO = 3%, while Figure 11b presents the flow pattern at the capillary inlet for this condition. When VO = 3% the orifice of the needle valve was around 0.04 mm. The pressure drop imposed on the refrigerant flow was so high that the acrylic dryer was filled with liquid. The acrylic sight glass, however, received a high frequency bubbly flow caused by refrigerant vaporization in the needle valve, making several vapor bubbles enter the capillary tube. The larger bubbles provided a separation between the liquid and vapor phases, leading to a high frequency slug flow at the capillary outlet, causing the acceleration of the evaporator inlet pipe to rapidly spike up and down.

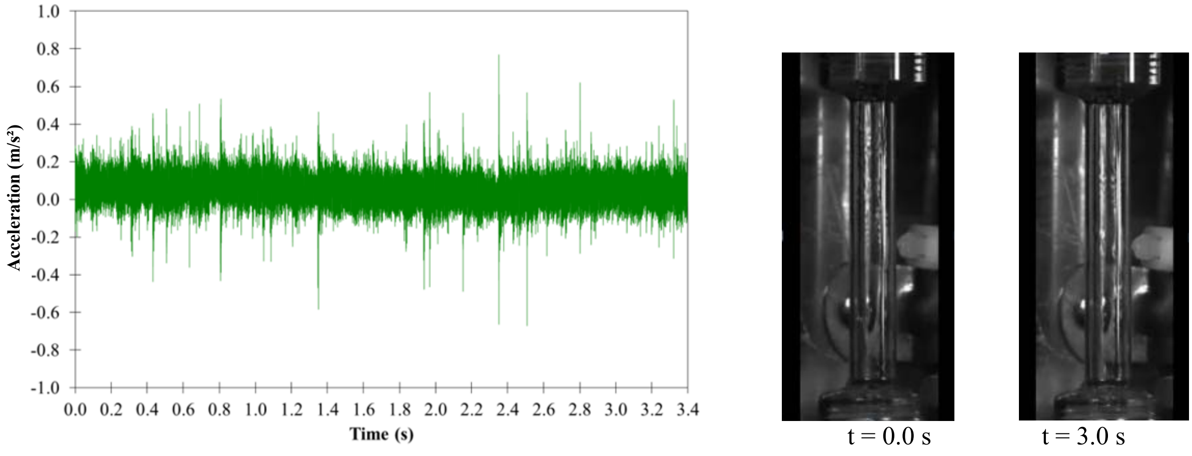
By observing the test results for VO = 3%, in which the acrylic dryer was filled with liquid, it can be inferred that if an equivalent diameter capillary tube was used – that is, a capillary tube with the same length as the original, but with a smaller inner diameter, so that the mass flow rate is the same as that obtained with the combination of the needle valve and the original capillary tube – a constant liquid flow would also be obtained at the entrance.



(a)

(b)

Figure 10: Acceleration readings for different VO values: (a) 100% and (b) 3%.



(a)

(b)

Figure 11: High speed accelerometer readings (a) and flow pattern at the FZ capillary inlet (b): VO = 3%.

The equivalent diameter of the needle valve-original capillary tube pair was measured by the N_2 volumetric flow rate method, according to the ANSI/ASHRAE 28-1996 standard. The constant values in the equation developed by Kipp and Schmidt (1961) were obtained from Boeng and Melo (2014) for a more precise diameter calculation. In addition, the algebraic model developed by Hermes *et al.* (2010) was used to predict the capillary tube inner diameter that would produce the measured compressor mass flow rate, considering the geometric and operational input data described in the previous section. Table 1 compares the results from the N_2 volumetric flow rate test and the value calculated by the algebraic model.

Table 1: Estimates for the capillary equivalent diameter.

Method	**Equivalent diameter [mm]**
N_2 volumetric flow – Kipp and Schmidt (1961) equation with Boeng and Melo (2014) parameters	0.53
Algebraic model – Hermes *et al.* (2010)	0.48

The predicted diameter of 0.48 mm is outside of the applicable range of the algebraic model and thus an error band of ±15% had to be considered. Therefore, in order to balance the compressor operation, the capillary must have an inner diameter in between 0.41 mm and 0.55 mm. Additionally the N_2 volumetric flow rate method yielded an inner diameter of 0.53 mm, close to the upper limit of the predicted value. However, the nitrogen does not change phase when flowing through the needle valve, which is the case when the needle valve-capillary tube pair is used in a real refrigerator. As discussed previously, this leads to a two-phase flow in the capillary inlet, reducing even further the refrigerant mass flow rate. In other words, the equivalent diameter derived from the N_2 volumetric flow rate method is higher than that required by the appliance.

For this reason, this work focused at the lower limit of the error band of the algebraic model. However, most refrigerator manufacturers resist using capillaries with inner diameters smaller than 0.50 mm. This is so because small unwanted particles and small amounts of air and water vapor may enter the refrigerator tubing in the production line. If the capillary inner diameter is smaller than 0.50 mm, the chances of it getting obstructed by these small particles or by tiny bits of frozen moisture are considerably increased. Hence, it is very hard to find 0.41 mm I.D. capillary tubes applied in refrigerators.

Instead, a capillary with an inner diameter of 0.45 mm replaced the needle valve-original capillary tube. The acrylic sight glass and the acceleration readings at the evaporator inlet pipe were monitored. No refrigerant charge adjustments were necessary, since the compressor mass flow rate was not altered by the change in the capillary tube. Figure 12 shows the acceleration profile for the evaporator inlet pipe obtained in this test. Unfortunately, due to hardware issues, it was not possible to record the flow pattern at the FZ capillary inlet. When Figure 12 is compared with Figures 5a and 11a, it is clear that a much smoother refrigerant flow pattern was obtained at the capillary inlet, leading to much lower evaporator inlet pipe accelerations. There are some concentrations of higher acceleration readings, but these are more widely distributed, indicating that a low frequency slug flow had occurred. More importantly, this confirms that the original capillary design was oversized and that the fluctuating noise was a consequence of the pseudo-steady refrigerator operation, which can be turned into a true steady state simply by using an adequate capillary tube, bringing the acoustic behavior of the refrigerator back to acceptable standards.

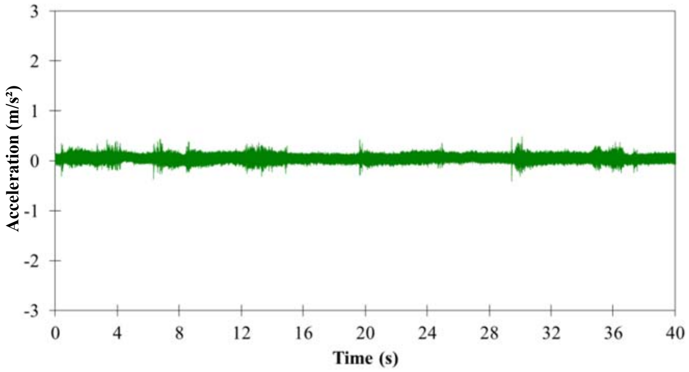


Figure 12: Acceleration readings: refrigerator equipped with 0.45 mm ID capillary tube.

4. CONCLUSIONS

In this paper an experimental study on the fluctuating noise phenomenon has been described. Thermodynamics and two-phase flow theory were used to obtain more tangible conclusions and generate a more solid discussion on the subject. Furthermore, it was possible to show the effects of the refrigerant flow pattern at the entrance of the capillary tube on the acoustic behavior of household refrigerators, contributing to the broad field of study which addresses expansion noise.

- The acoustic behavior of most household refrigerators is greatly affected by the flow pattern at the inlet of the capillary tube. The more oscillating this flow pattern is, the stronger the evaporator vibrations will be. Since the evaporator is a good sound radiator, the noise generated by the highly pulsating two-phase flow at the exit of the capillary will be audible outside the appliance.
- The capillary tube was submitted to a transient operation regime due to its oversizing, providing a mass flow rate higher than that displaced by the compressor. Due to this unbalanced design the refrigerant flow at the capillary inlet was characterized as slug flow, being discharged into the evaporator inlet pipe as a highly pulsating two-phase flow.

- A needle valve was installed immediately before the capillary tube to increase the restriction of the expansion device. As the valve was closed, smoother flow patterns were obtained at the capillary inlet, softening the vibrations of the evaporator. However, since the refrigerant pressure drop through the needle valve was too abrupt, vaporization occurred before the entrance of the capillary, producing a bubbly flow in that region.
- A much smoother, yet not completely homogeneous, flow at the capillary inlet could be obtained with a smaller capillary tube diameter, without compromising the performance of the refrigerator. The ideal situation of completely liquid flow at the entrance of the capillary would be obtained only by using tubes with even smaller diameters, which are very difficult to find and whose installation by refrigerator manufacturers is currently considered impracticable.

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