Flow-Induced Noise in Refrigerators

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ABSTRACT

Vibration and noise problems due to fluid flow occur in many refrigerators. This phenomenon obstructs smooth plant operation. The flow-related vibrations are known as "Flow-Induced Vibrations". In the case of piping connected to reciprocating fluid machines, the oscillating (fluctuating) flow generates excitation forces causing to piping vibration. "Flow-Induced Vibrations" cause to "Flow-Induced Noise", known as "Fluctuating Noise". In a refrigerator, refrigerant-induced noise is a combination of fluid-acoustic and vibro-acoustic phenomena. One of the importance sources of the flow-induced noise in refrigerators is two-phase flow at the evaporator inlet. In this study, capillary position design of the evaporator inlet is analysed. Capillary insert length is varied and the effect of this modification is examined by noise tests. The modification results in the abatement of the flow-induced noise.

Keywords: Flow-induced noise, Fluctuating noise, Refrigerator, Two-phase flow

1. INTRODUCTION

Turbulence, compressor-induced pulsations, phase change and throttling are the main sources of acoustic excitation in the refrigerant flow (1). In this study the phase change of the refrigerant flow is examined. Before proceeding with this subject, the refrigeration system, its components and flow-induced vibrations will be outlined.

1.1 Refrigeration System

Refrigeration is the process of removing heat from a lower-temperature zone and discarding it to a higher-temperature zone. Heat naturally flows from hot to cold zones. Refrigeration is therefore the opposite of the natural flow of heat. A refrigeration cycle shown in Figure 1 is composed of four processes: Compression, condensation, throttling and evaporation.

1.2 Refrigeration System Components

A typical refrigeration system is shown in Figure 2. System has five basic components: Compressor, condenser, expansion valve, evaporator and refrigerant fluid.

Compressor: This component draws the low-temperature, low-pressure vapor from the evaporator via the suction line. Then transforms this vapor into a high-temperature, high-pressure vapor. After, pushes this vapor into the condenser coils on the outside of the refrigerator.

Condenser: The high-pressure refrigerant vapor from the compressor is then cooled to the point where it becomes a liquid refrigerant within the condenser. In liquid form at high pressure, the refrigerant absorbs the heat and cools down the air inside the fridge and freezer. The liquid refrigerant then flows from the condenser into the liquid line.

Expansion valve: The high-pressure liquid from the condenser reaches to the expansion valve. The valve then reduces the pressure of the refrigerant as it passes through the orifice, located inside the valve. On reducing the pressure, the temperature of the refrigerant also decreases to a level below the surrounding air. In this throttling process, a two phase (liquid + vapor) flow is produced and directed to the evaporator.

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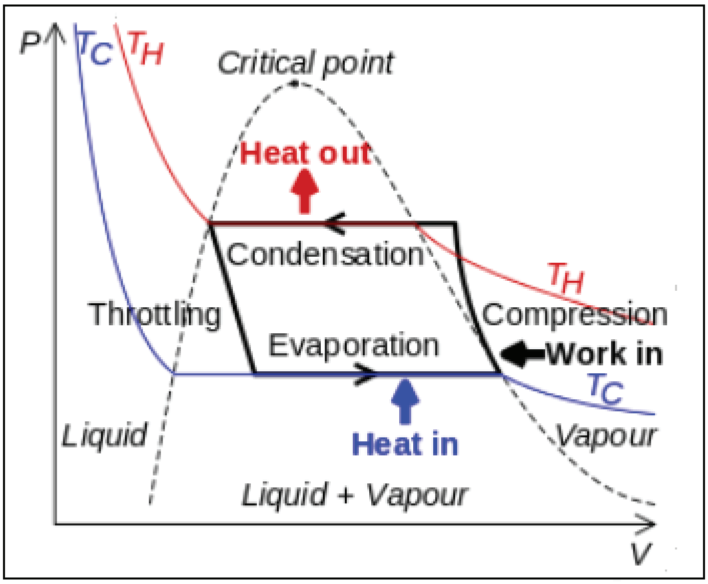

Figure 1. A fictitious pressure-volume diagram for a typical refrigeration cycle (2).

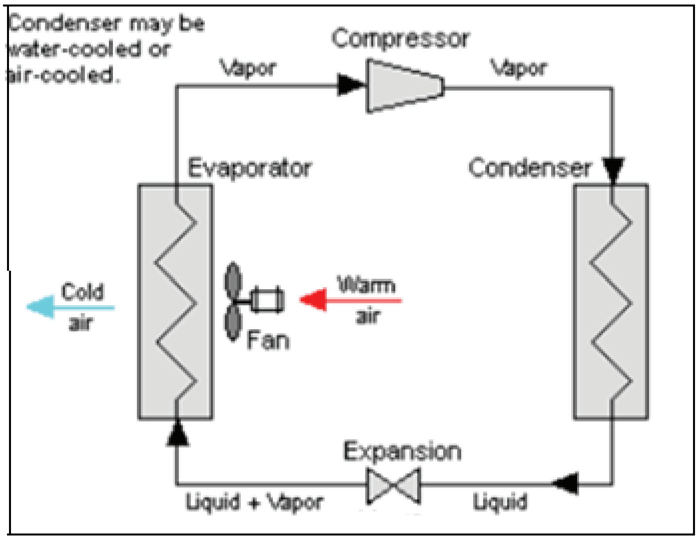

Figure 2. A schematic view of the refrigeration system (2).

Evaporator: The cold mixture is directed to evaporator coils through capillary tubes to be vaporized again. Evaporator absorbs heat from the surroundings. This procedure is supported by a fan unit. The refrigerant directed from expansion valve to evaporator is in low temperature and low pressure. Therefore, heat of air inside the fridge and freezer is transferred to the refrigerant. The refrigerant begins to boil under low pressure. The level of this pressure is determined by two factors:

-The rate at which the heat is absorbed from the product to the liquid refrigerant in the evaporator.

-The rate at which the low-pressure vapor is removed from the evaporator by the compressor.

-Refrigerant fluid: The refrigerant fluid is an inert gas used principally as a "high-temperature" refrigerant for the refrigeration system.

1.3 Flow-Induced Vibrations

S. Kaneko et al. (3) have presented a classification based on flow type as given in Table 1. Flow-induced vibrations arise due to steady, unsteady and two-phase flows. Single-phase flow does not cause to vibration. For steady flow, the interaction between fluid and structure causing to increase in vibration amplitudes is the most commonly observed phenomenon. For unsteady flow, turbulent forces constitute dominant source of structural vibration excitation. Two-phase flow is a mixture of two fluids with different densities. Therefore, the variations of flow momentum and pressure in time are sources of excitation for the structural vibration.

Table 1. Classification of Flow Induced Vibration (3).

Fluid and flow	**Flow field**	**Vibration mechanism**	**Example**
Single-phase flow			
Steady flow	External flow	vortex induced vibration	resonant vibration
			forced vibration
		acoustic resonance	acoustic resonance
			cavitation
		fluidelastic vibration	wing flutter and galloping
			fluidelastic vibration of tube arrays
	Internal flow	surging	compressor surge
			pump surging
		vibration of piping	piping, bellows, collapsible tubes
Unsteady flow	Turbulent flow	random vibration	buffeting
			vibration of reactor internals
	Sudden change in flow	pressure pulsation	valve vibration
			water hammer
	Pulsating flow	forced vibration	vibration due to internal fluid oscillations
		acoustically induced vibration	combustion-induced vibration
Two-phase flow	Bubble-induced vibration		sloshing
	Thermal-hydraulic vibration with phase change		vibration caused by condensation
			instability caused by boiling
	Vibration of piping by two-phase flow		

Some definitions and explanations about vibration mechanisms in Table 1 are given below:
Vortex – induced vibration: VIV is the motion induced on bluff bodies interacting with an external flow. This resonance phenomenon occurs when the vortex shedding frequency of the oscillating flow becomes close to one of the structural frequencies of the body.
Acoustic resonance: This situation may occur in heat exchangers and boilers with tube bundles. When a critical level of the flow rate in the duct is exceeded acoustic resonance may occur. A high level of noise is produced, in extreme cases preventing plant operation and causing structural damage.
Fluidelastic vibration: This phenomenon, also known as self-induced oscillations, is observed for multiple cylinders. When the flow velocity is high, cylinders oscillate with large amplitudes. This is the most dangerous vibration and the main cause of many problems in industry.
Surging: This is a particular pressure pulsation mode in pipeline systems containing turbomachinery. Surging may occur in a pipeline if a tank or an accumulator is located downstream of the pump and a resistive component, such as a flow-regulating valve, is located further on downstream. When the fluid contains many air bubbles, the bubbles can play the same role as installed accumulators.
Vibration of piping: Oscillating and two-phase fluid flows are causes of pipe vibrations. Gas-liquid two-phase flow producing vibration may have different flow patterns shown in Figure 3 and explained as following:

- Bubbly flow: In this situation, the flow – induced forces are small and the gas flow rate is low. Therefore, bubbles occur in main liquid flow in the pipe as shown in Figure 3.a. A unit bubble can be modeled as a single degree of freedom system (4, 5). The equation of motion and natural frequency of the bubble are given in Table 2.
- Stratified flow and wavy flow: In the case of horizontal piping liquid collocates at the lower side and gas flows at the upper side. If the interfacial surface is smooth, the flow is called a stratified flow (Figure 3.b). If interfacial surface is wavy, the flow is called a wavy flow (Figure 3.c).
- Plug flow and slug flow: If the equivalent radius of the bubble is larger than the radius of the pipe the spherical shape of the bubble deforms (Figure 4). In this case bubbles may be in bullet shape. This flow is called plug flow (Figure 3.d). If large bubbles and liquid slugs flow alternately, this flow is known as slug flow (Figure 3.e).
- Froth flow: In this case, liquid slugs contain many bubbles but their shapes are not uniform. This flow is highly turbulent so flow-induced forces are large (Figure 3.f).
- Annular mist flow: This flow consists of an unstable liquid flow at the bottom and gas flow at the center of the piping. The turbulence in the liquid flow may cause to pipe vibrations (Figure 3.g).
- Mist flow: The main flow is the gas flow and liquid droplets flow like mist. This flow is the opposite of the bubbly flow (Figure 3.h).

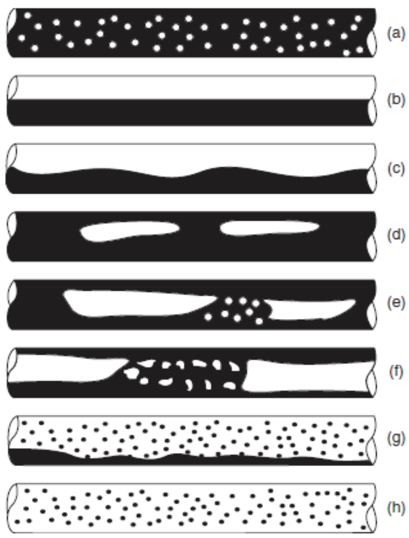

Figure 3. Flow patterns in horizontal pipes: (a) bubbly flow, (b) stratified flow, (c) wavy flow, (d) plug flow, (e) slug flow, (f) froth flow, (g) annular mist flow, (h) mist flow (3).

Table 2. Vibration characteristics of bubble

Strasberg (4)	$m\ddot{v} + b\dot{v} + k(v - V_0) = P_A e^{j\omega t}$ where, $m = \frac{\rho}{4\pi R_0}$, $k = \frac{\gamma p}{V_0}$ and $v = V_0 + \alpha \sin\frac{2\pi t}{T}$ m: equivalent mass of the bubble v: the volume of the bubble b: radiation resistance of the bubble k: equivalent stiffness of the bubble V_0: initial volume of the bubble R_0: equivalent radius of the bubble P_A: acoustic pressure of the bubble ω: radius frequency t: time ρ: density of the liquid surrounding the bubble γ: specific heat ratio p: pressure of the liquid surrounding the bubble α: amplitude of oscillation T: period of oscillation
Minnaert (5)	$f_n = \frac{1}{2\pi R_0}\sqrt{\frac{3kp}{\rho}}$ f_n :natural frequency of the oscillating bubble

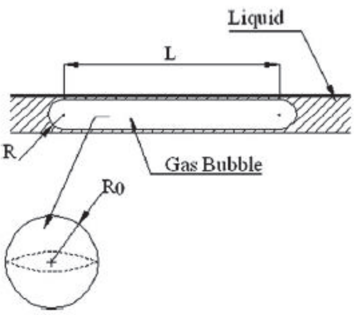

Figure 4. Deformation of the bubble (7)

Forced vibration: As self-excited vibration, forced vibration is an important cause of pressure pulsations. Pulsations damage to machines and plants directly and may cause secondary damage to surroundings.
Acoustically induced vibration: Thermal processes such as combustion, steam condensation and boiling are causes of acoustic vibration and noise.
Random vibration: Vibration is considered random when it doesn't conform to the vortex-induced or fluidelastic vibrations. This phenomenon includes the excitation due to vortices generated by upstream structures.
Pressure pulsation: Flow in a piping generally is random. However a specific frequency component

may become dominant when flow changes due to effect of fluid machinery. If this frequency equals to the acoustic natural frequency of any equipment, then high flow oscillations and related pressure pulsations occur. This phenomenon is also known as "flow oscillations".

1.4 Flow-Induced Noise

Flow induced noise has become one of the key factors on household refrigerators especially in recent years. Therefore, this subject is being examined and discussed increasingly in the open literature.

Han et al. (6), have presented a study on the root-causes of refrigerant-induced noise in refrigerators. They concluded that bubbles in an intermittent flow have the most important effect on this noise. Therefore, flow patterns in region of two-phase flow should be considered. The flow pattern may be made steady by increasing mass flux or mass flow rate. These cycle conditions are especially important in the evaporator inlet pipe.

Han et al. (7), have examined the flow pattern of the refrigerant in an evaporator-inlet pipe; and estimated flow patterns also using different maps. They monitored the characteristics of the flow in their experiments. They discussed the relation between the flow pattern and flow-induced noise; and suggested the shape and layout of the evaporator-inlet to keep away from intermittent flow pattern.

Hartmann and Melo (8), have presented an experimental study on popping noise in a refrigerator. Popping noise is a type of flow-induced noise that occurs after some short time of the compressor start-up. The main cause of this strange and unpleasant noise has been explained by "condensation induced shock". Authors have made some attempts to decrease this noise. The popping noise is completely eliminated when the dryer is positioned horizontally. But this solution is not suitable for applying to all refrigerators. The other effective solution is using heat exchanger. They concluded that this solution had benefit to eliminate the flow noise and the energy consumption of the appliance didn't change.

Hartmann and Melo (9), have made an experimental study on capillary tube flow. They used a dual-evaporator, bottom-mount refrigerator with a variable speed compressor. The research was focused on the effects of the flow pattern at the entrance of the capillary tube on the acoustical behavior of household refrigerators. They noticed the high speed, two-phase flow on the capillary inlet tube of the evaporator and examined oscillating, coalescing and collapsing vapor bubbles produced in the flow. They made different attempts to attenuate the fluctuating noise by producing steady, single phase flow at the capillary inlet and concluded that using capillary tubes with smaller diameters might be a solution. However their supply was limited and also installations were not practical.

Neto et al. (1), have analyzed fluid borne noise in refrigerators with experimental study. They have measured the acoustic pressure and the acceleration signals on different points. They have found that the main source of acoustic excitation is the pulsations of the compressor. The other cause of the refrigerant-induced noise was the high-speed superheated flow creating turbulent excitation. High-intensity spikes due to vapor bubbles were at the entrance of the capillary tube. They recommended smaller radius tubing to recover the noise due to two-phase intermittent flow. Acoustic filters at the suction and discharge pipes of the compressor and also at the exit of the capillary tube were their other recommendations.

2. MODIFICATION OF THE CAPILLARY TUBE

Capillary tube is the inlet part of the evaporator. Acoustic behavior of the household refrigerators is greatly affected by the flow pattern of the capillary tube. Oscillation of the flow pattern causes to evaporator vibrations. When evaporator is vibrating severely, noise may be noticeable from the outside of the appliance. Therefore, the flow at the inlet and outlet of the capillary tube is significant for the vibration and noise of the refrigerator. In Figure 5, the capillary tube inlet of the evaporator is shown.

The previous studies have investigated the capillary geometry, mass velocity, mass quality of the refrigerator and bubble geometry. Since two-phase flow at the evaporator inlet is an important source of the flow induced noise in refrigerators, the design of the capillary should be effective on this physical phenomenon. The main idea supporting this research relies on this fact on which no published work is present.

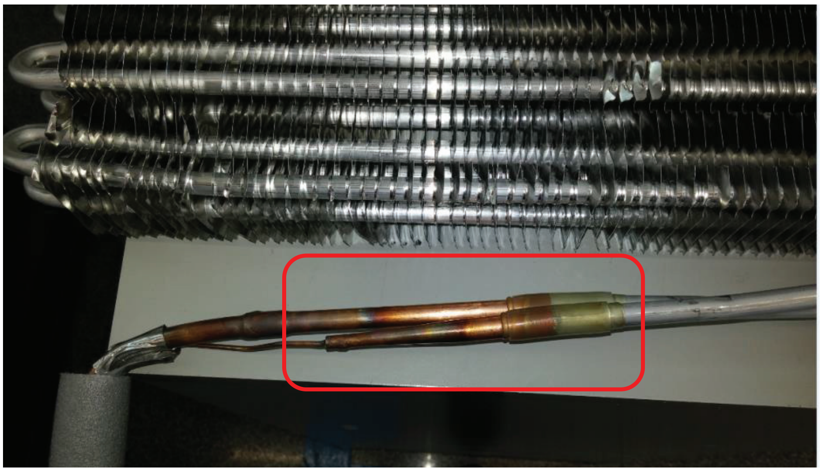

Figure 5. Capillary tube inlet of the evaporator.

In the course of this flow-induced noise study, the effect of the capillary position design was examined by varying capillary insert length (Figure 6). The refrigerator was a typical no frost, bottom-mount type, equipped with 1600 rpm compressor, running with the use of R-600a as refrigerant. In this refrigerator capillary position is horizontal.

It was observed that the original capillary length of the refrigerator with flow induced noise was short. Therefore, the two-phase flow at the evaporator inlet was being directed to a narrow cross sectional area. Refrigerant was striking the walls exerting high levels of noise. For this reason, some design changes were applied to increase the capillary insert length. In order to recover the flow characteristics and also flow-induced noise, samples with different capillary lengths were produced and these were assembled to the same appliance. Then, acoustic tests were performed for these refrigerators.

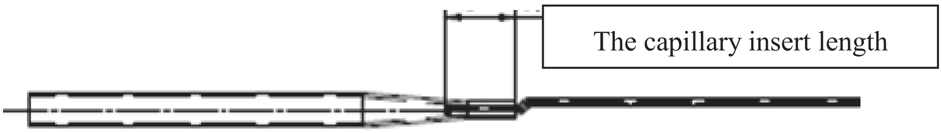

Figure 6. The capillary position of injection area.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Appliance was placed in a reverberation chamber with background noise 25 dB(A) and cut-off frequency 100 Hz. The sound power level was determined with three microphones, installed in the reverberation chamber. The frequency range of sound measurement was up to 10 kHz. In order to determine the relationship between the noise and cycle conditions, electric power level was determined simultaneously with the cycle temperature. For this purpose, two T-type thermocouples and a data logger were used.

The first acoustic tests were performed for the refrigerator with original capillary length (7 mm). The result was obtained in a fluctuating shape as shown in Figure 7. The mean sound power level was 39.8 dB(A) with ± 2.5 dB(A) fluctuations between the compressor start-up and up-down periods. The acoustic behavior was unsteady and large fluctuations proceed along all the compressor time. Figure 8 shows the variation of the cyclic temperature and electric power of the refrigerator at the operating time. Sound power level variation in time and its 1/3 octave frequency spectrum are shown together in Figure 9. Equivalent level was obtained as 39.8 dB(A). It can be noted that the flow-induced noise has wide frequency content and there are considerable contributions in the range of 200 Hz-1000 Hz.

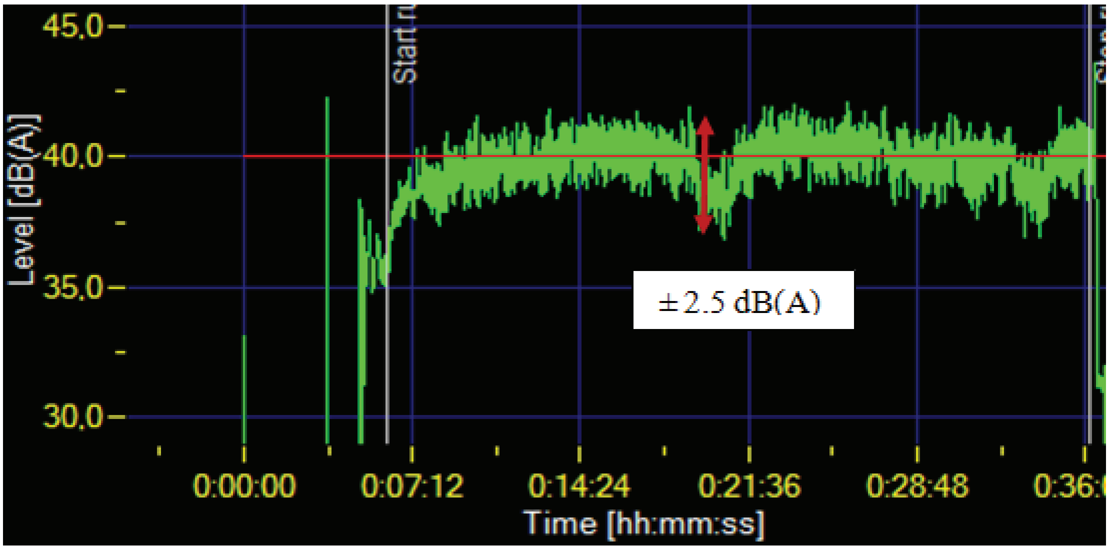

Figure 7. Sound power level variation of the refrigerator.

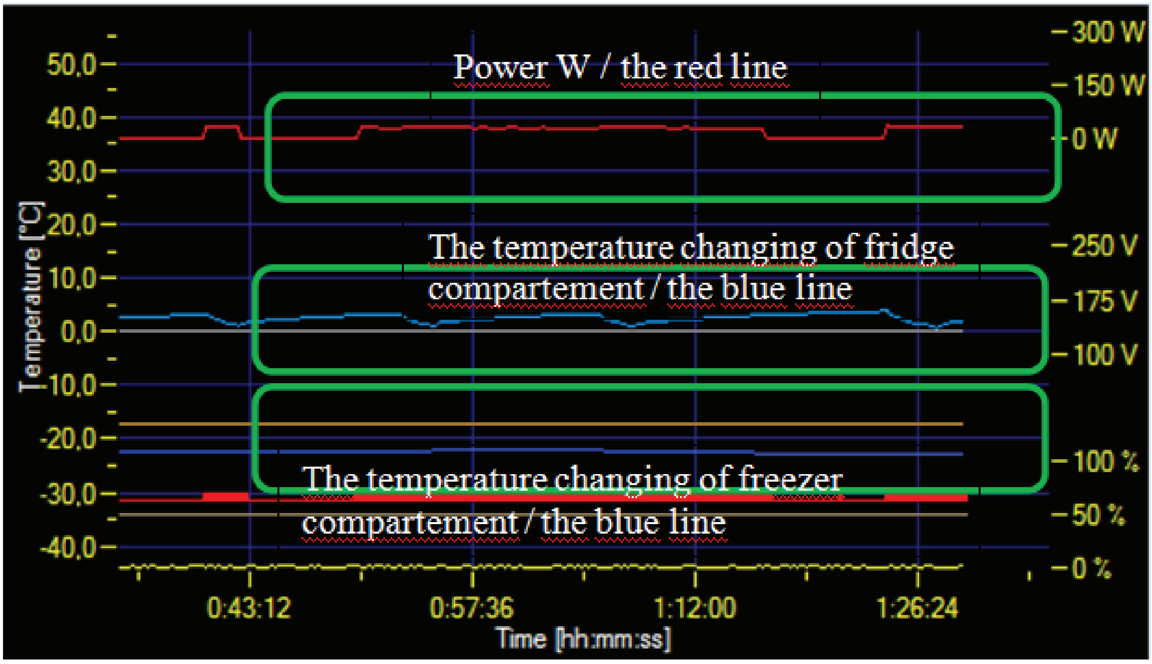

Figure 8. The cyclic temperature and electric power of the refrigerator.

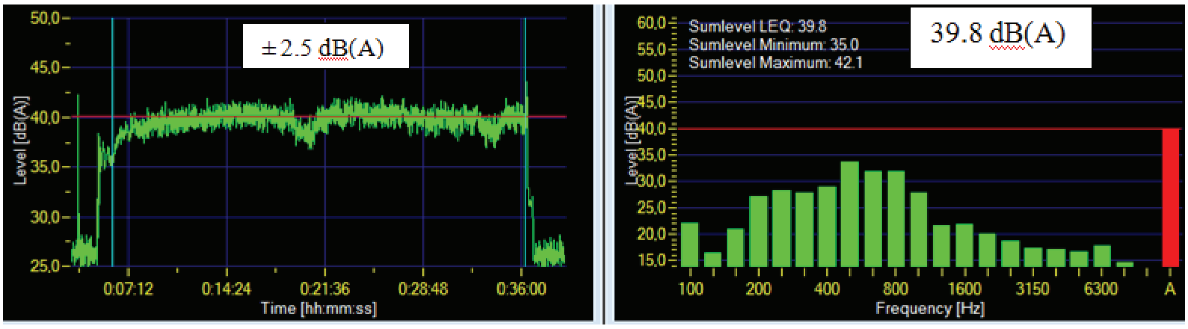

Figure 9. Sound power and frequency spectrum for the capillary insert length 7 mm.

The fluctuations of sound power indicate that the noise is mainly due to flow. Nevertheless, the compressor and fan noise level should be investigated in order to gain a better understanding of the flow induced part of the noise. Therefore, the compressor and fan of the refrigerator were subjected to solo noise level measurements. The results of the measurements are shown in Figures 10 and 11 as overall sound power level dB(A) and 1/3 octave band spectrum. As it is seen, compressor and especially fan have narrow frequency bands.

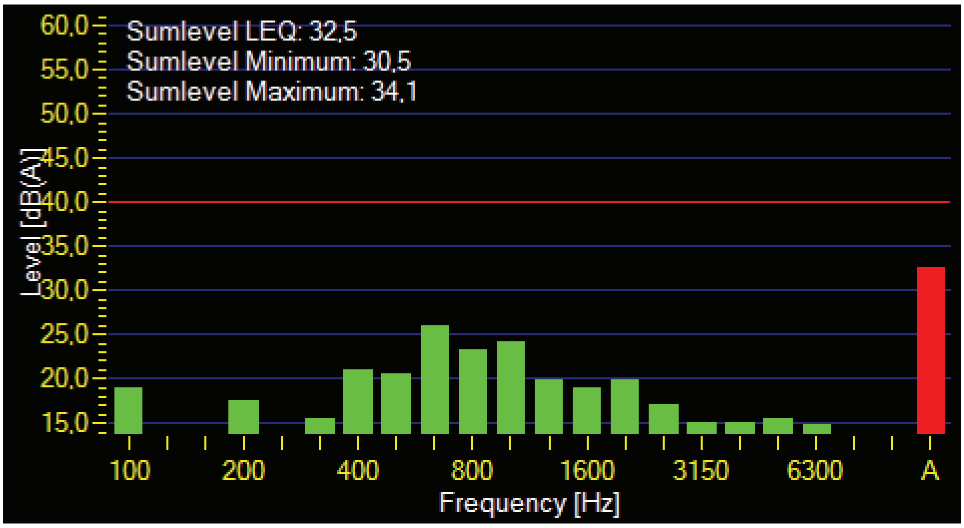

Figure 10. Solo compressor sound power level and frequency spectrum.

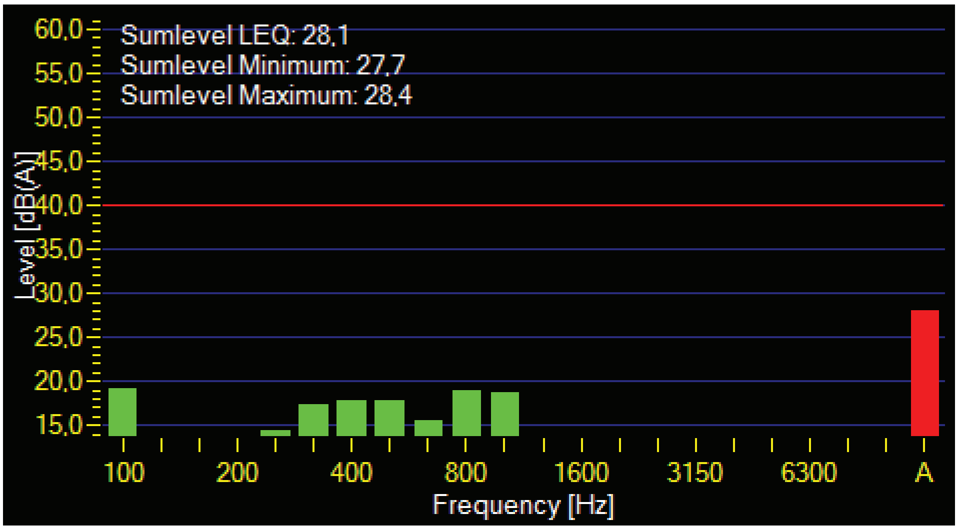

Figure 11. Solo fan sound power level and frequency spectrum.

Using the decibel summation formula to obtain the total sound power level of the compressor and fan,

$$L_A + L_B = 10\log_{10}(10^{\frac{L_A}{10}} + 10^{\frac{L_B}{10}}) \qquad (1)$$

where,
L_A: The solo compressor sound power level - 32.5 dB(A)
L_B: The solo fan sound power level - 28.1 dB(A)
$L_A + L_B$ = 33.84 dB(A)
is obtained. Consequently, the difference between the total sound power level 39.8 dB(A) and the total solo level 33.84 dB (A) gives the contribution of the flow noise.

In order to examine the flow-induced noise, three different samples were prepared and tested. These samples have capillary insert lengths of 15 mm, 17 mm and 20 mm. The sound power variation levels and 1/3 octave frequency spectra of the refrigerators with these samples are shown in Figures 12, 13 and 14, respectively. Abstract of the measurement are presented in Table 3. Results show the positive effect of increasing capillary insert length on both the level and variation of the sound. The fluid induced noise has been completely recovered for the capillary tube with 20 mm insert length. For this case, the measured level 34.0 dB(A) is only the combined noise of the compressor and fan. Also, this noise is almost steady with negligible variation.

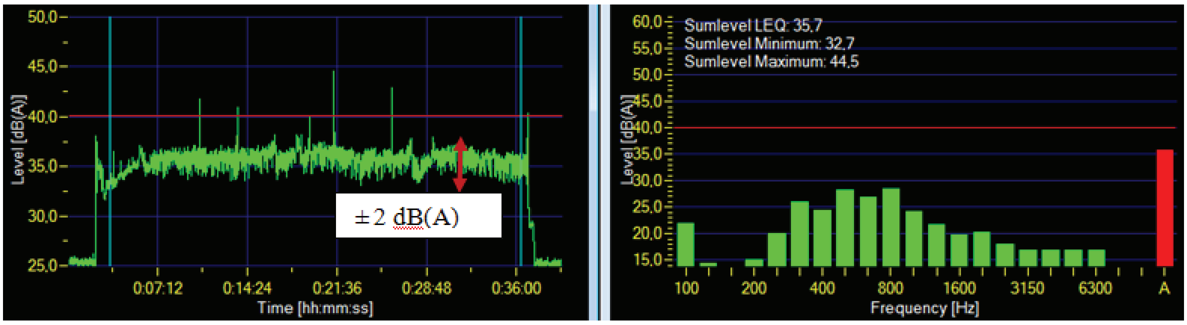

Figure 12. Sound power and frequency spectrum for the capillary insert length 15 mm.

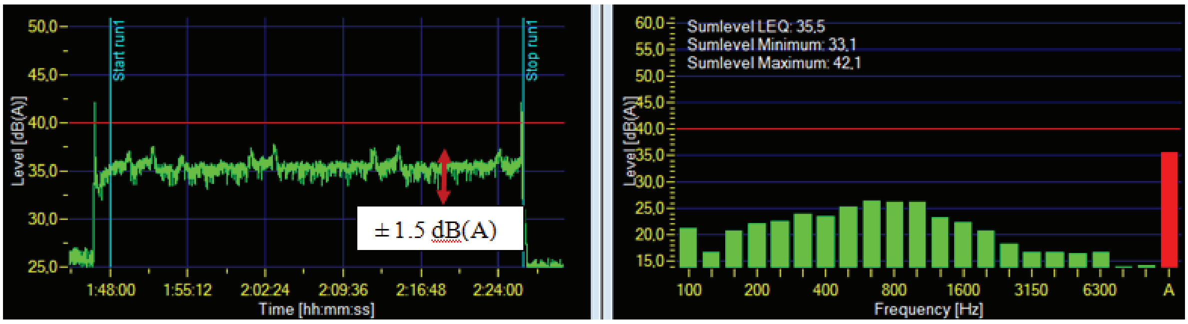

Figure 13. Sound power and frequency spectrum for the capillary insert length 17 mm.

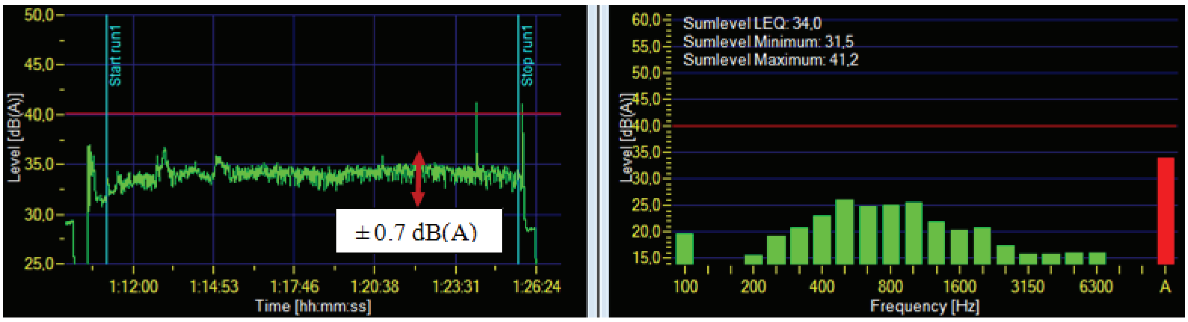

Figure 14. Sound power and frequency spectrum for the capillary insert length 20 mm.

Table 3. The abstract of measurements for different capillary insert lengths

Measurement	**The capillary insert length (mm)**	**Sound Power Level dB(A)**	**The variation of sound power level dB(A)**
1	7	39.8	± 2.5
2	15	35.7	± 2.0
3	17	35.5	± 1.5
4	20	34.0	± 0.7

4. CONCLUSIONS

- One reason of the flow induced noise is throttling of the refrigerant passing through the capillary insert of the refrigerator system. This process produces a two-phase flow which can even reach critical conditions in terms of acoustic behavior.

-In order to control the flow induced noise of the refrigerator, the capillary design was improved by elongating capillary insert length at the evaporator inlet.

-The new capillary insert length got benefits by completely eliminating the flow-induced noise of the refrigerator.

-The variation of sound power level with time was almost disappeared by this modification.

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