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Characteristics and control of popping noise in the refrigerator with R600a

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ABSTRACT

The popping noise in the refrigerator is the most common noise problem. The popping noise is caused by the condensation-induced shock inside the capillary tube. The system's performance influences the occurrence of popping noise. In this paper, an R600a vapor-compression cycle is utilized to study the properties of popping noise in the refrigerator. The system is a mock-up system of an existing refrigerator system. The system is placed in a semi-anechoic chamber with a high-frequency microphone setup. This paper discusses the characteristics of popping noise in different operating conditions. The amplitude of the popping noise was determined by the shock wave caused by the bubble collapsing, which is hard to control. The most effective way to control popping noise is to reduce the number of bubbles collapsing inside the cap tube. Therefore, the main principle of popping noise mitigation is heat transfer control between the capillary tube and the suction line. A linear correlation between popping noise loudness and the heat transfer between the cap tube and suction line is given in the paper.

1. INTRODUCTION

The capillary tube and the suction line are always in contact together to function as the internal heat exchanger in the refrigerator system. The internal exchanger can improve the system performance by further subcooling the refrigerant before entering the evaporator. However, the internal heat exchanger consisting of a capillary tube and the suction line can cause severe noise problems. For one thing, the flow regime at the beginning of the capillary tube is slug flow, according to Lorbek *et al*. (2020). Wang *et al*. (2016) studied the coalescence of liquid droplets. The heat transfer between the suction line and capillary tube can cause the vapor bubbles at the beginning of the capillary tube to recondense and collapse. Under these circumstances, the condensation-induced shock can happen in the internal heat exchanger and cause severe noise issues when using the refrigerator. Hartmann and Melo (2013) showed that the popping noise caused by condensation-induced shock is related to the temperature difference between the suction line and capillary tube inlet using an accelerometer for noise measurements. Therefore, by installing an extra internal heat exchanger, the popping noise could disappear. Nevertheless, the quantitative relationship between popping noise and system conditions was not shown by Hartmann and Melo (2013).

Although the capillary tube inlet is always subcooled, the non-equilibrium two-phase refrigerant flow at the subcooled temperature is typical in the refrigeration system. Lee *et al*. (2016) found that a thermodynamic non-equilibrium flow coexists with the subcooled gas, and subcooled liquid exists in an 18 C subcooled region. Also, the vapor bubbles can enter the capillary tube through the dryers when the liquid level inside reaches the upper edge of the capillary tube (Hartmann and Melo, 2013). The existence of vapor bubbles and the heat transfer between the capillary tube and suction induces a popping noise. Popping noise in the refrigerator is now a common noise issue and can cause great annoyance to the occupants.

This paper discusses the relationship between popping noise and thermal conditions. Also, a model related to the loudness of noise and the thermal conditions is shown. The paper provides a more comprehensive view of popping noise analysis. Therefore, the result of this paper provides future guidance to avoid popping noise near the internal heat exchanger in the refrigerator.

2. METHODOLOGY

As shown in Figure 1, the suction line cools the liquid inside the cap tube and causes the bubble to shrink. The bubbles are supposed to shrink into smaller ones or collapse in the end. The temperature $(T_0 - T_1)$ drives the bubble in the capillary tube to shrink and collapse. The bigger the temperature difference is, the more the bubble wall velocity accelerates. In other words, the temperature difference determines the occurrence of the condensation-induced shock. The temperature difference is determined by the heat transfer between the cap tube and the suction line. And the mass flow rate inside the cap tube is another factor that influences the temperature difference. Therefore, the amplitude of popping noise should be proportional to the heat transfer between the cap tube and the suction line.

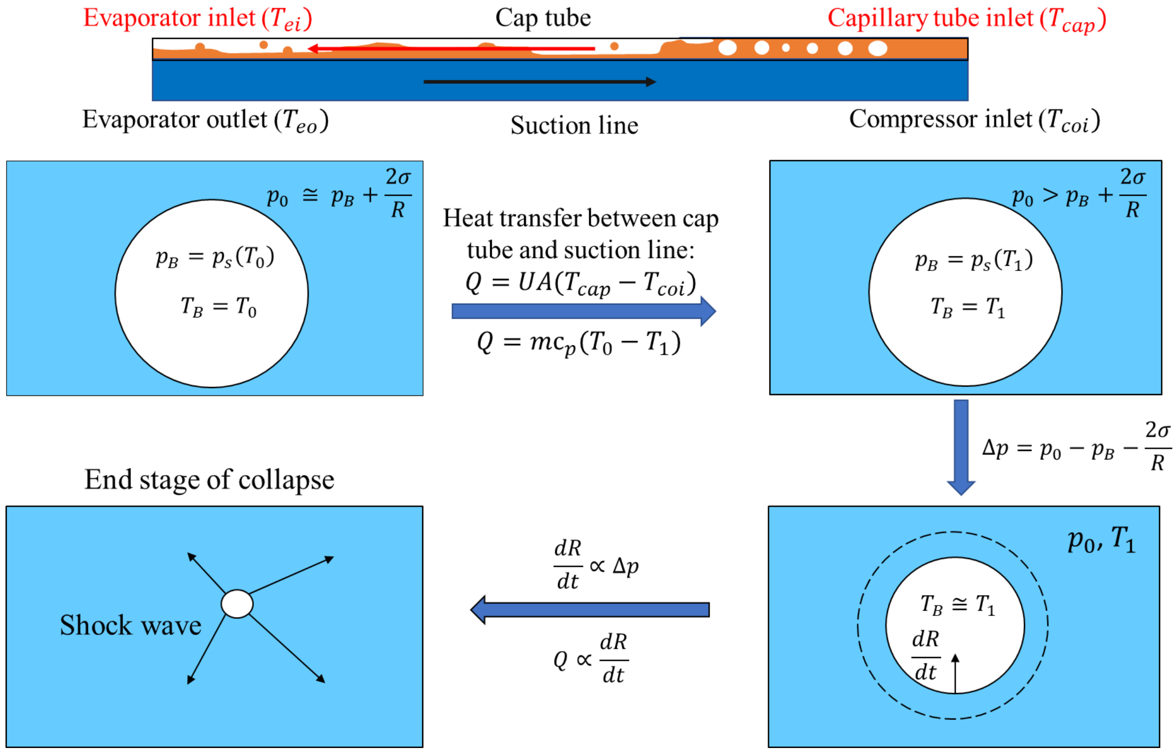


Figure 1. The principle of condensation induced shock.

The following assumptions are made for estimating the heat transfer between the capillary tube and suction line:
(1) The enthalpy remains the same from the drier outlet to the position where the cap tube begins contacting the suction line.
(2) The heat transfer coefficient at the capillary tube side is calculated based on the two-phase heat transfer model in the microchannels, as shown in equations (1) to (7) (Choo and Kim, 2011):

$$Nu_{tp} = 0.023 Re_l^k \, Pr_l^{0.4} \, F \tag{1}$$

$$k = 0.8 - 0.8\left(1 + e^{\frac{d^* - 37}{7}}\right)^{-1} \tag{2}$$

$$F = C \cdot X^{-n} \tag{3}$$

$$n = 0.7 - 0.8\left(1 + e^{\frac{d^* - 41}{2}}\right)^{-1} \tag{4}$$

$$C = 2.94 + 358e^{-0.1d^*} \tag{5}$$

$$X = \frac{1-x}{x}\sqrt{\frac{\rho_v}{\rho_l}} \tag{6}$$

$$d^* = \frac{D}{\sqrt{\frac{\sigma}{\rho}}} \tag{7}$$

(3) The pressure before the cap tube contacts with suction line is equal to the local saturation pressure in the cap tube when the condensation-induced shock happens.

(4) The mass flow rate of the system can be estimated by the evaporation temperature and condensation temperature. The mass flow is calculated based on the compressor performance data. The correlation between the mass flow and the system performance is shown in equation (8):

$$m = 4.8 \cdot 10^{-4}\rho_{suc} - 1.55 \cdot 10^{-5}(\rho_{dis} - \rho_{suc}) \tag{8}$$

For sound evaluation, loudness is used to evaluate the amplitude of the noise. By dividing the sensitive human audible frequency range (20 Hz and 15.5 kHz) into 24 barks, the definition of loudness is defined in equation (9) (Fastl and Zwicker, 1999):

$$\mathrm{L} = \int_0^{24\mathrm{Bark}} \mathrm{N}'(\mathrm{z})\mathrm{dz} \tag{9}$$

The sound pressure level describes the amplitude of sound at a certain frequency, while the loudness describes the overall subjective perception of flow-induced noise within a period. The relationship between the average sound pressure level and the loudness within a period is given in equation (10):

$$\mathrm{SPL} = 30 + 33.2\mathrm{log10}(\mathrm{L}) \tag{10}$$

The relationship between the sound power and sound pressure level is shown in equation (11):

$$\mathrm{SPL} = 10\mathrm{log10}\left(\frac{\mathrm{W_{so}}}{\mathrm{W_{ref}}}\right) \tag{11}$$

Where $\mathrm{W_{ref}} = 10^{-12}W$. It can be speculated that the sound power should be linearly proportional to the loudness of the noise.

3. EXPERIMENTAL SETUP

Figure 2(a) shows that an R600a refrigeration system is built to mock a refrigerator system. A compressor is used to provide the pressure difference. The location of thermocouples and the pressure transducer is also shown in the system schematic. Figure 2(b) shows that an unfrozen part appears in the suction line when the system is running because of the heat transfer between the capillary tube and the suction line. The temperature of R600a in the suction line is below zero, so the water stream in the air froze when reaching the suction line.

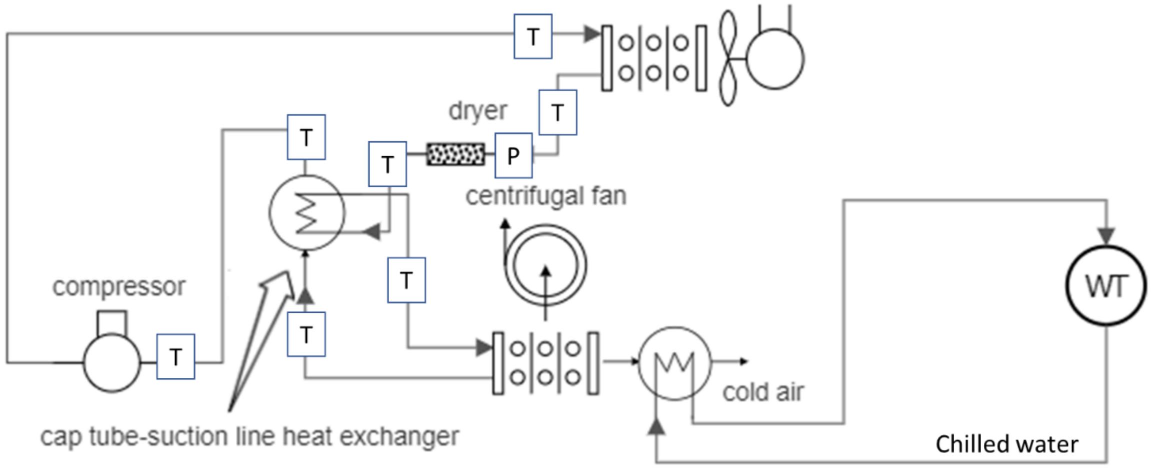
However, when the suction line contacts the capillary tube inlet, the high temperature inside the capillary tube melts the ice on the suction line, and the unfrozen part appears. Therefore, when the heat transfer region ends, the frost appears again. In this case, two thermocouples are installed at the suction line, one is at the heat transfer region near the capillary tube inlet, and another is at the compressor inlet. In Figure 2(c), the compressor and the condenser are placed on the top of the system, and a control board regulates the compressor speed and the fan speed. The compressor speed varies from 1500rpm to 4500rpm. The compressor speed is usually 4500 rpm for a refrigerator system. In Figure 2(d), a chilled water loop is used to provide the cold air that is directed back to the evaporator region. The centrifugal fan is used to pull the cold air through the evaporator. The chilled water temperature is about 5℃. With the help of the chilled water loop, the energy generated by the compressor can be removed. Figure 2(f) shows a shield placed in front of the evaporator and functions as the air duct to direct the airflow. Also, the shield with some insulation creates a cold chamber near the evaporator. The evaporator temperature can reach -10℃ with this experimental setup.

The sampling rate for the noise measurements is 44.2 kHz. The time-domain data is half of the sampling rate after being converted to the frequency domain. Thus, half of the sampling rate should cover the human audible range. There are 6 thermocouples (Type T) and one pressure transducer (PX 309) in the experiment. A summary of uncertainties is shown in Table 1.

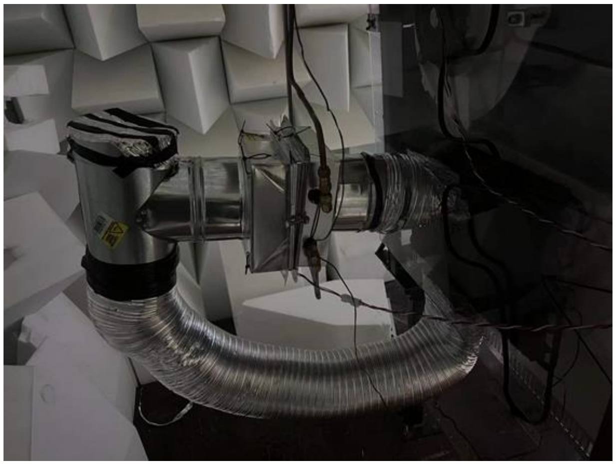
Table 1. Summary of measured and calculated property uncertainties

Type	Measured properties		Calculated properties		
Properties	Temperature (℃)	Pressure (kPa) (relative uncertainties)	Quality (-)	Q (W)	$\dot{m}$ (kg/s)
Uncertainties	0.5	0.25%	0.005	0.8	$7.844 \cdot 10^{-7}$

(a)



(b) (c)



(d) (f)

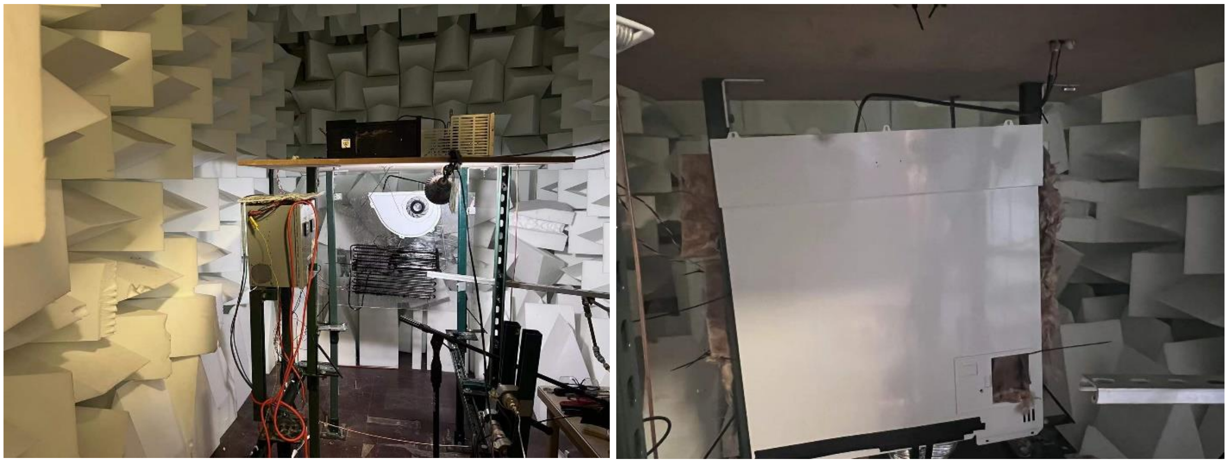


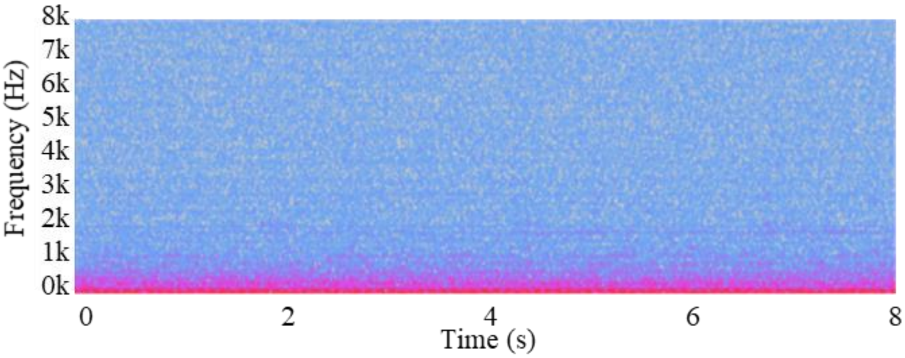
Figure 2. System schematic and experimental setup

4. RESULTS AND DISCUSSION

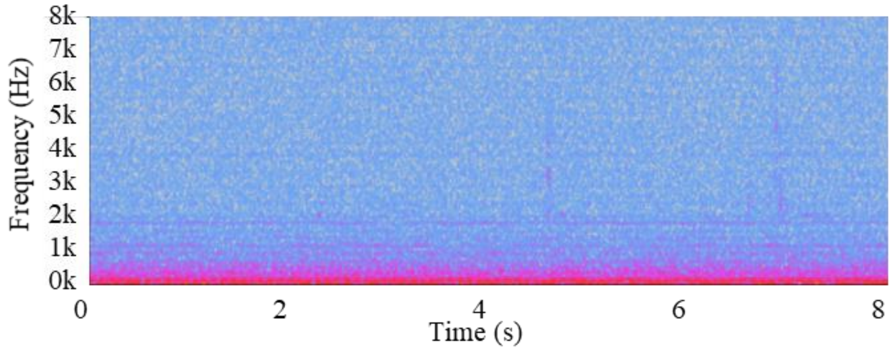
In Figure 3, it is shown that the popping noise disappears when the system charge increases. When the system charge decreases to 65.5g, the popping noise appears. When the charge is about 53.5g, the popping noise happens frequently. The higher system charge leads to a higher system mass flow rate. With the same heat transfer Q, the temperature difference ($T_0 - T_1$) is smaller with a higher system charge. The temperature difference results in the recondensation of the bubbles inside the capillary tube. The smaller the temperature difference, the less frequent the condensation-induced shock. Thus, the popping noise is less severe. Therefore, one way to eliminate the popping noise is to increase the system charge. However, increasing system charge results in higher system pressure, limited by the system capacity.

The system charge is set to 53.5g to study the characteristics of the popping noise. From Figure 4, the length of the unfrozen part is linearly proportional to the heat transfer between the suction line and the capillary tube. The temperature inside the suction line determines the unfrozen length of the suction line and capillary tube. The temperature of R600a in the suction line is determined by the heat transfer between the suction line. The more the capillary tube heat the suction line, the longer the unfrozen length is. The result in Figure 4 gives a good correlation between the length of the unfrozen part and the heat transfer between the cap tube and the suction line. In Figure 5, the relationship between the sound power of popping noise and the heat transfer to the vapor flow (xQ) is shown. For one thing, a bigger heat transfer to the vapor flow leads to a higher temperature difference ($T_0 - T_1$). The higher temperature difference leads to a more frequent popping noise. The higher temperature difference also results in a more severe shock wave at the end stage of collapsing. Therefore, the sound power of the popping noise should increase as the heat transfer to the vapor flow increases. It is validated that the loudness of popping noise is linearly proportional to the heat transfer to the vapor flow inside the capillary tube in Figure 5.

(a) charge=68g



(b) charge=65.5g



(c) charge=53.5g

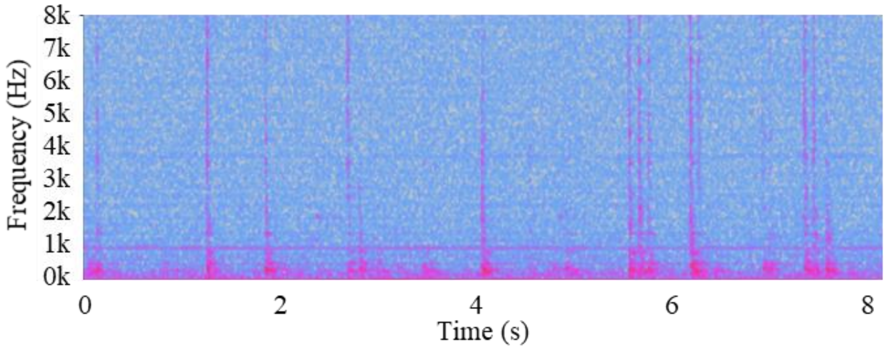


Figure 3. Occurrence of popping noise with different system charge

Another way to control the popping noise should be to control the heat transfer between the cap tube and suction line. For example, a possible way to eliminate the popping noise could be by reducing the contact length between the cap tube and suction line so that the heat transfer between the suction line and the cap tube is reduced. The results of which would be validated in the future.

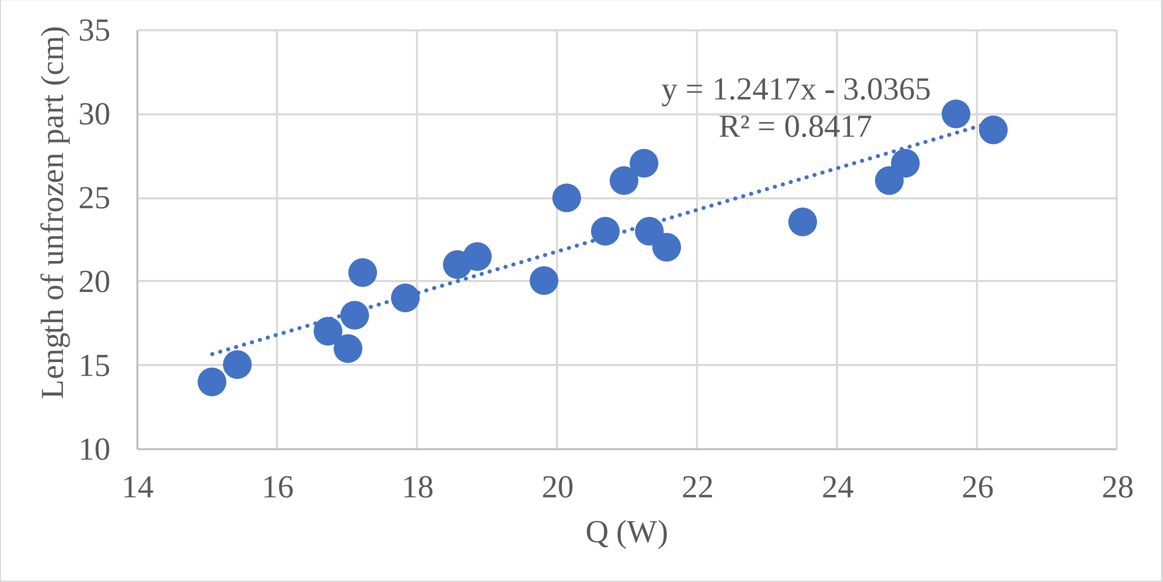


Figure 4. The relationship between the length of the unfrozen part and the heat transfer Q between the suction line and the capillary tube

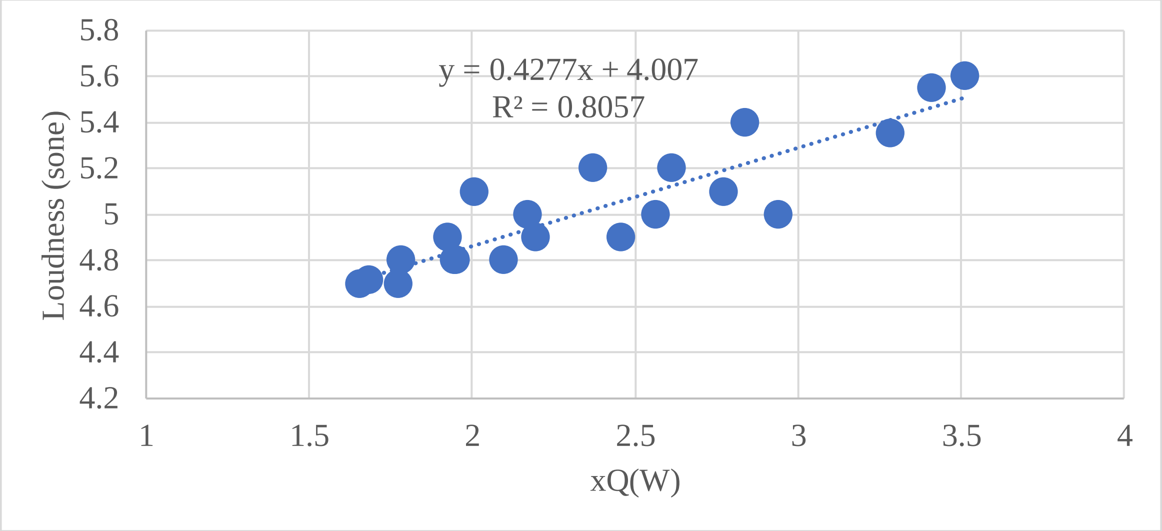


Figure 5. The relationship between the loudness of popping noise and the energy transferred to vapor flow in the capillary tube

5. CONCLUSIONS

This paper shows a study about how the system conditions influence popping noise. The internal heat exchanger consists of a capillary tube and suction line, which is the main reason for the popping noise. The suction line cools the cap tube and causes the recondensation of vapor bubbles. The shock wave is generated at the end of the bubble collapsing and therefore cause the popping noise. The total sound power of the popping noise is related to the heat transfer between the cap tube and the suction line. More system charge leads to a higher system mass flow rate and smaller temperature reduction in the cap tube. Therefore, the popping noise disappears when the system charge increases. Also, the loudness of the popping noise is linearly proportional to the heat transfer to the vapor flow. Also, the length of the unfrozen part is linearly proportional to the total heat transfer between the cap tube and the suction line. Therefore, there are two possible ways to control the popping noise: (1) increase system charge; (2) reduce contact length between suction line and cap tube.

NOMENCLATURE

Symbols:		
T	temperature	(C)
p	pressure	(kPa)
Q	heat transfer between cap tube and suction line	(W)
R	bubble radius	(m)
SPL	sound pressure level	(dB)
x	vapor mass fraction (quality)	(-)
Re	Reynolds number	(-)
Nu	Nusselt number	(-)
Pr	Prandtl number	(-)
L	loudness	(sone)
N'	loudness density	(sone bark^{-1})
W	power	(W)
z	bark number	(-)
UA	heat transfer coefficient	(W K^{-1})
m	mass flow rate	(kg s^{-1})
c_p	specific heat	(J $kg^{-1}K^{-1}$)
t	time	(s)
Subscripts:		
cap	capillary tube inlet	

coi	compressor inlet	
tp	two phase	
so	sound	
s	saturate	
l	liquid	
B	bubble	
dis	discharge	
suc	suction	
Greek:		
ρ	density	(kg m^{-3})

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