

Flow-Induced Gurgling Noise in Automotive Refrigerant Systems

Zhengyu Liu, Donald Wozniak, Manfred Koberstein, Curtis Jones, Jan Xu, and Suhas Venkatappa
Ford Motor Co.

ABSTRACT

Refrigerant flow-induced gurgling noise is perceived in automotive refrigerant systems. In this study, the condition of the gurgling generation is investigated at the vehicle level and the fundamental root cause is identified as the two-phase refrigerant flow entering the TXV for system equipped with variable displacement compressors. By conducting literature reviews, the acoustic characteristics of the flow patterns and the parameters affecting the flow regimes in horizontal and vertical tubes are summarized. Then the gurgling mechanism is explained as the intermittent flow is developed at the evaporator inlet. In the end, the improved and feasible design for avoiding the intermittent flow (slug, plug or churn flow) or minimizing its formation is proposed and verified in refrigerant subsystem (RSS) level. Finally, the guidelines for the attenuation and suppression of the gurgle are provided.

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INTRODUCTION

Controlling refrigerant flow-induced noises generated from automotive air-conditioning (A/C) systems is one of the major climate control system related NVH issues. The resolution of the NVH usually requires much more development time and cost increment.

Since significant progress has been achieved on the control of the major noise sources such as powertrain NVH, road NVH and windnoise, the traditionally secondary noise sources such as refrigerant flow-induced hiss and flow noise become more audible than before. Therefore, it is desired by customers to reduce the refrigerant flow-induced noises.

Refrigerant flow-induced noises by the automotive A/C system (with TXV) are generally classified into three categories [1]:

1. Thermal expansion valve (TXV) related noises: (1) broadband high frequency hiss ($> 1000\text{Hz}$); (2) trumpeting noise ($500\text{Hz} \sim 1200\text{Hz}$ and its harmonics)
2. Evaporator related noises: (1) transient whistling tones ($700 \sim 4000\text{Hz}$) from top manifold tubes or/and plate-fin type flow channel; (2) Stationary flow noise (sounds like low speed fan noise, $> 1000\text{Hz}$); and (3) evaporator tubes related transient/high-pitched whistling tones ($6.0\text{ kHz} \sim 11.0\text{ kHz}$)
3. A/C line charge port related high-pitched whistles [1-2]

Besides the above flow-induced transient noises, recently gurgling noise was identified during one vehicle development. The definition of the verb "gurgle" from Merriam-Webster dictionary is "to make a sound like a liquid boiling or bubbling", while the verb "hiss" is

defined as to produce a sound like a long "s". Therefore, the refrigerant flow-induced gurgling noise sounds different from the refrigerant flow-induced hiss noise.

The gurgling noise can cause dissatisfaction for critical customers. However, based on authors' knowledge and literature review, little work has been done on the generation mechanism, acoustic characteristics and attenuation of the gurgling noise in automotive A/C system [1, 2, 3, 4, 5].

In this study, the relationship between ambient condition and audible gurgling noise are first investigated on R134a A/C system equipped with variable displacement compressor in vehicle level. The flow development, acoustic characteristics of the flow patterns, and the flow regimes in horizontal and vertical tubes are summarized based on the literature review. The gurgling mechanism is explained as the intermittent flow is developed at the evaporator inlet.

In the end, to attenuate the audible gurgling noise, the improved and feasible design for avoiding the intermittent flow is proposed and verified in refrigerant sub-system (RSS) level. Finally, the guidelines for the attenuation and suppression of the gurgle are provided.

GURGLING NOISE MECHANISM

The refrigerant system under study is equipped with TXV and externally-controlled variable displacement compressor (EVDC). The EVDC changes the swash-plate angle to manage the refrigerant displacement in accordance with cabin, ambient and driving conditions.

Vehicle Level Gurgling Noise Generation Condition and Investigation

During one vehicle program development, a just noticeable refrigerant gurgling noise was perceived with the climate control system running at A/C compressor engaged, lowest blower speed, and outside air mode after vehicle stopped for a few seconds. It was noticed that the audible gurgling noise mostly occurs when the ambient temperature is below 18°C, especially between 10°C ~ 16°C range.

To better understand the issue, the vehicle and refrigerant system are instrumented. To monitor the thermodynamic condition (Mollier diagram), the A/C system high/low pressures, and the temperatures of evaporator, TXV inlet tube surface, condenser outlet tube surface, and ambient are measured along with Power Control Module (PCM) data including compressor current, engine speed and engine cooling fan speed. Uni-axial accelerometers are also mounted on the suction and liquid tubes close to TXV, and microphone headset of HEAD acoustics SQuadriga™ is on driver's head.

Figure 1 shows the vibration data on the suction and liquid tubes close to TXV from one driving event. The ambient temperature was at 12°C, and the climate control system was set at 22°C in outside airflow mode.

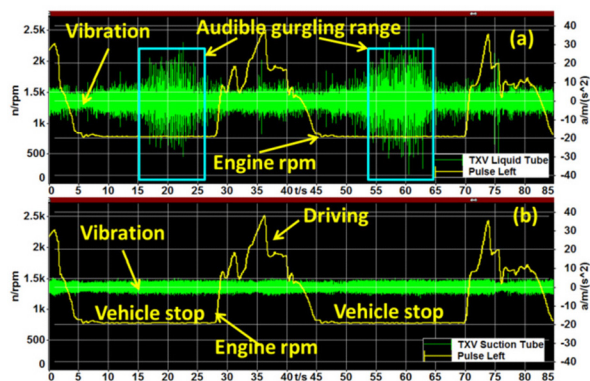


Figure 1. Suction and liquid tube vibration data during driving & stop events: (a) Liquid tube vibration/engine rpm vs. time, (b) Suction tube vibration/engine rpm vs. time.

It is observed from Figure 1 that (1) the audible gurgling noise was perceived several seconds after vehicle fully stopped; and (2) the vibration level on liquid tube close to TXV increases significantly when gurgling noise occurs, but the vibration level on the suction tube exhibits minor change. Based on this observation, it can be concluded that the gurgling source is in liquid tube side close to TXV.

Figure 2 shows another test result with ambient temperature at 14°C, and the climate control system was set at 21°C in outside airflow mode. Both subjective and objective assessments were conducted during drive evaluation. In the first stop time range ①, only very slightly audible gurgle was perceived, while in the second and third stop time ranges, ② and ③, clearly audible gurgling noise exhibited. Analyzing Figure (b) it is noticed the TXV inlet refrigerant flow subcool (SC) is around 0.0°C in time range ①, but the subcool is below 0.0°C in time range ② and ③.

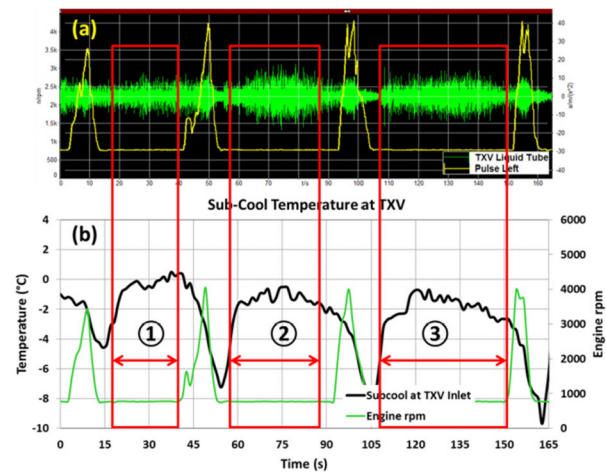


Figure 2. Liquid tube vibration data and TXV Inlet subcool during driving & stop events: (a) Liquid tube vibration/engine rpm vs. time, (b) TXV Inlet subcool vs. time/engine rpm vs. time.

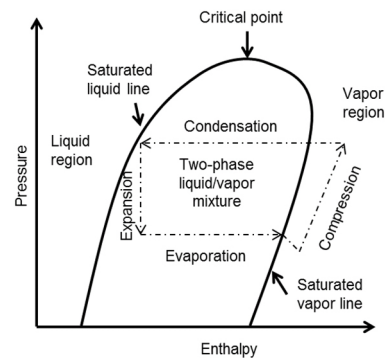


Figure 3. Refrigerant pressure-enthalpy diagram

Based on the refrigerant pressure-enthalpy diagram (known as Mollier diagram, Figure 3), the refrigerant flow entering the TXV is in the status of saturated two-phase mixture of liquid and vapor in the time range ② and ③.

It is believed the two-phase refrigerant flow entering the TXV results into gurgling noise when vehicle stops at idling.

Refrigerant Flow Patterns between TXV and Evaporator Inlet

Because of assembly, service and safety concerns, TXV is usually not directly attached to the evaporator, but located on firewall or dash panel, so there is significant distance (120mm or longer) between the two components. Also, various tube orientations (horizontal or vertical) between TXV and evaporator inlet due to packaging issue.

Based on Fei and Hrnjak's study [6] on the R134a two-phase refrigerant flow development using a transparent horizontal PVC tube between expansion valve and evaporator using single-phase flow at TXV inlet [6], the whole flow is divided into three regions: expansion region, developing region and fully developed region.

In the expansion region, both phases exhibit homogenous flow pattern (droplet type, bubble/droplet type, and bubble type, Figure 4). The developing region is a transition stage from expansion to the