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An Experimental Study on the Performance of Inverter Heat Pump with a Variation of Frequency and Capillary Size

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Key Words : Inverter heat pump, Capillary tube, Optimum cycle

Abstract

An experimental study was performed to investigate the optimum cycle of an inverter heat pump as a function of frequency. The performance of the inverter heat pump with the rated cooling capacity of 4,141W(3,550kcal/h) was measured with a variation of frequency, indoor and outdoor temperature, and length of capillary tube in the psychrometric test room. As a base case, the inverter heat pump with the standard capillary length of 1,000mm(optimum size for the frequency of 60Hz) and ASHRAE Test condition "A" was tested by varying frequency from 30Hz to 80Hz. Then, the optimum cycles were investigated by varying the length of capillary tube at each frequency level of 30, 60 and 80Hz. Based on the experimental data, the change of system characteristics between the optimum and the base case were analyzed for each selected frequency level. Generally, for low frequency level(30Hz), the longer length of the capillary tube compared with the standard size showed the higher energy efficiency ratio(EER), while for high frequency level(80Hz) the shorter length of the capillary tube showed the higher EER.

1. Introduction

A constant speed heat pump modulates capacity of a system through on/off control of a compressor with respect to building load, and the ratio of running time of the system, that is the ratio of on-time to off-time, is proportional to building load.(1) The average efficiency of the system is reduced because of the loss occurring through on/off operation of the compressor.

An inverter heat pump makes it possible to operate a compressor continuously by capacity modulation of a system with respect to building load utilizing frequency control of a

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compressor. It also provides several advantages in energy conservation, capacity control, and comfort of indoor environment.(2,3) In addition, the balance point between building load and capacity of inverter heat pump in the heating mode can be lowered compared with a constant heat pump at the increased compressor speed of a system. Thereby the peak electric power consumption is reduced because the required auxiliary heating capacity decreases.(3)

Due to the several advantages of inverter heat pump, it possesses 40% of heat pump market in Japan since 1990, and the demand is increasing continuously. However, inverter heat pump is not widely used in Korea due to the lack of understanding. Production of inverter heat pump in Korea will be significantly increased due to the comfort of indoor environment and energy saving.

In association with inverter heat pump, the following several topics have been vigorously studied : low noise, low vibration, high efficiency scroll compressor(4), and design modification of a system with application to HFC-alternatives.

In this study, the performance of an inverter heat pump with cooling capacity of 4,141W(3,550kcal/h) was measured with a variation of frequency, length of capillary tube, and indoor and outdoor temperatures. Then the optimum cycle was investigated by varying the length of capillary tube at each frequency level of 30, 60, and 80Hz.

Based on the experimental data, the change of performance of a system with a capillary tube as an expansion device was analyzed to investigate that it was operated at the optimum condition. The requirements of an expansion device for optimum operation in a cycle with a variation of frequency was investigated. Finally the basic concepts to develop an expansion device that enhances the efficiency of an inverter heat pump were proposed.

2. Experimental Setup and Test Procedure

A schematic diagram of the experimental setup to test an inverter heat pump is shown in Fig.1. It consisted of indoor and outdoor rooms. Each room was equipped with an air handling unit for controlling both temperature and humidity. It was utilized to permit precise measurement of temperature and humidity of sampling air at the inlet and outlet of an indoor unit. Air flow rate through the indoor unit was calculated by measuring differential pressure between the inlet and outlet of the nozzle, absolute pressure, nozzle exit temperature, and humidity at the nozzle. Figure 2 shows the schematic of the air flow chamber.

The test unit was a split type inverter heat pump with cooling capacity of 4,141W(3,550kcal

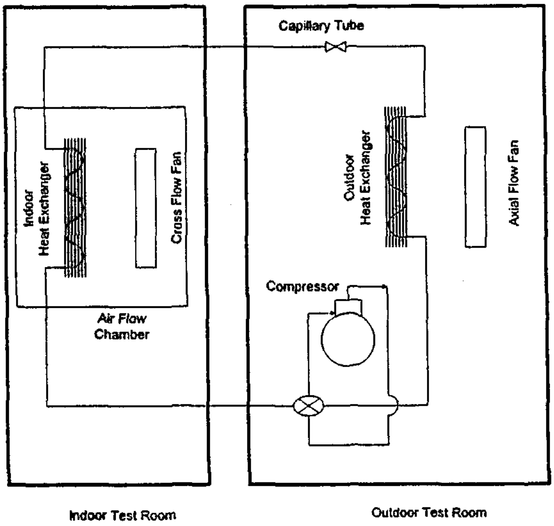

Fig.1 Schematic of refrigeration test loop

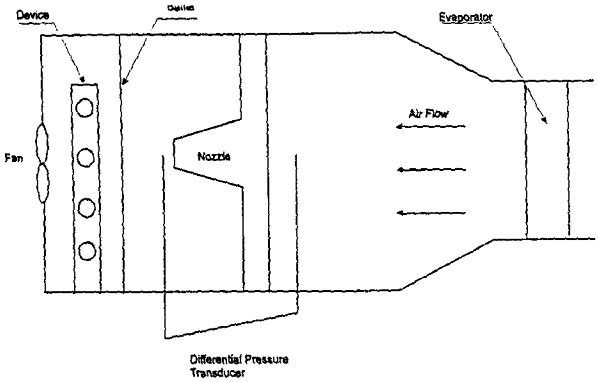

Fig.2 Schematic of duct system

/h). It used a single rotary compressor. The indoor unit was a finned-tube heat exchanger with 3-path structure of 2-row and 14-stage. The outdoor heat exchanger was composed of 2-path structure of 2-row and 24-stage. The capillary tube was used as an expansion device. The test was performed by changing the length of capillary tube and frequency of inverter heat pump. The amount of refrigerant charge to the system maintained constant throughout all test conditions. Therefore, the test was executed at the charge amount of 1,250g that showed the maximum performance at ASHRAE condition "A".

The characteristics of the inverter heat pump were examined through measuring the pressure, temperature, refrigerant flow rate, and power consumption of compressor and fan. The performance test of the inverter heat pump was carried out in two parts. First, the characteristics of the system were measured with the variation of frequency of the compressor and the length of capillary at a fixed indoor and outdoor condition. Second, the inverter heat pump was tested by varying the indoor and outdoor conditions at 60Hz. R-22 was used as a working fluid of the system. The test was executed in the cooling mode.

The standard capillary tube showing the maximum performance at the rated frequency (60Hz) under the ASHRAE test condition "A" was selected. The standard capillary tube has 1,000mm length and 1.7mm diameter. The performance of the inverter heat pump with the standard capillary tube was measured at each frequency level of 30, 60, and 80Hz with ASHRAE test condition "A". The performance test of the inverter heat pump was carried out continuously by varying a capillary tube length at the fixed capillary diameter(1.7mm). The cycle that represents the maximum energy efficiency ratio(EER) was choosen as the optimum cycle, and the characteristics of that was compared with the other cases. Then, performance test of the inverter heat pump with the capillary tube length of 950mm and 1,000mm at the frequency level of 60Hz was performed with the variation of indoor and outdoor conditions(Table 1).

Table 1 Test conditions

Frequency (Hz)	Capillary Length(mm)	Indoor Temperature(℃)		Outdoor Temperature(℃)	
		Dry Bulb	Wet Bulb	Dry Bulb	Wet Bulb
60	1,000, 950	27	19.5	27	24
30, 60, 80	620, 950, 1,000, 2,200	27	19.5	35	24
60	1,000, 950	27	19.5	43	25.5
60	1,000, 950	21	15.5	35	24
60	1,000, 950	32	22.5	35	24

3. Results and Discussion

3.1 The characteristics of an inverter heat pump with a variation of indoor and outdoor conditions

The performance of an inverter heat pump was tested with a variation of indoor and outdoor conditions and capillary tube length at the frequency level of 60Hz. The cycle variation according to capillary length was analyzed. Cycle variations of the system in accordance with a variation of indoor and outdoor conditions were investigated. The characteristics of the optimum cycle showing maximum EER were compared with those of standard capillary tube(diameter of 1.7mm, length of 1,000mm)

Figure 3 shows cooling capacity and power of the inverter heat pump with the capillary tube length 1,000mm at the frequency level of 60Hz as a function of indoor temperature. As the indoor temperature increased, both cooling capacity and power of the system increased. The EER also increased because the increasing rate of cooling capacity was larger than that of power consumption.

Figure 4 represents variation of the thermodynamic cycle of the system with the standard capillary tube as a function of indoor temperature. As indoor temperature increased, both evaporating pressure and condensing pressure slightly increased. As a result of an increment of condensing pressure and subcooling at the inlet of capillary according to the increase of indoor temperature, refrigerant flow rate and capacity of the system increased. Power consumption rose due to an increase of superheat and pressure at the compressor inlet, but the increasing rate of power consumption was lower than that of cooling capacity. When indoor temperature increased from 21℃db, 15.5℃wb to 32℃db, 22.5℃wb, cooling capacity increased by 20.7% from 3,564.8W to 4,304.3W and power consumption of the system increased by 3.4% from 1,506.4W to 1,557.0W.

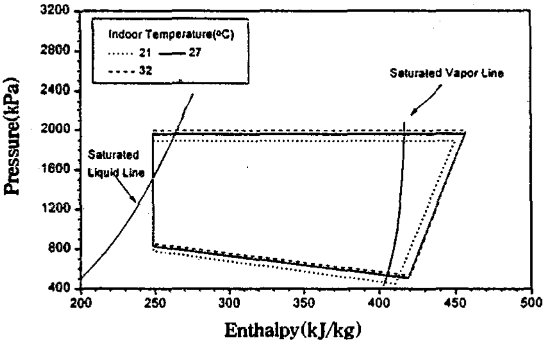

Fig.4 Pressure-enthalpy diagram with a variation of indoor temperature at 60Hz

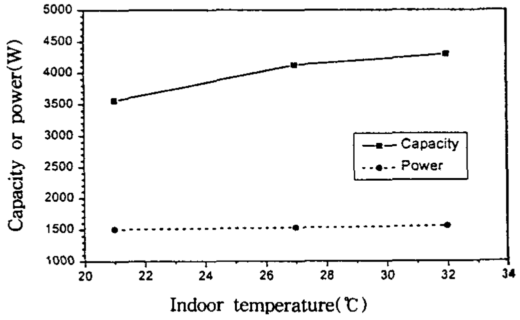

Fig.3 Capacity and power input as a function of indoor temperature at 60Hz

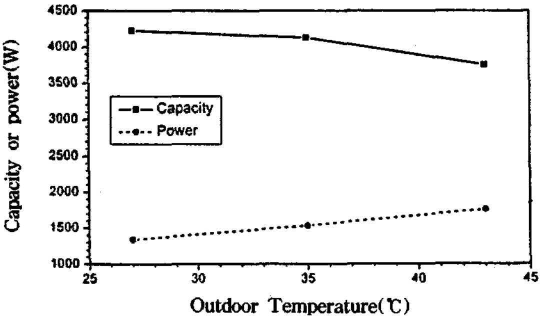

Fig.5 Capacity and power input as a function of outdoor temperature at 60Hz

Consequently, EER was enhanced by 16.5%.

Figure 5 represents the cooling capacity and power consumption of the system as a function of outdoor temperature with the 1,000mm capillary and the indoor temperature of 27℃db, 19.5℃wb. As outdoor temperature increased, power consumption increased, but cooling capacity decreased. As a result, EER of the system decreased.

Figure 6 shows variation of cycle of the system as a function of outdoor temperature.

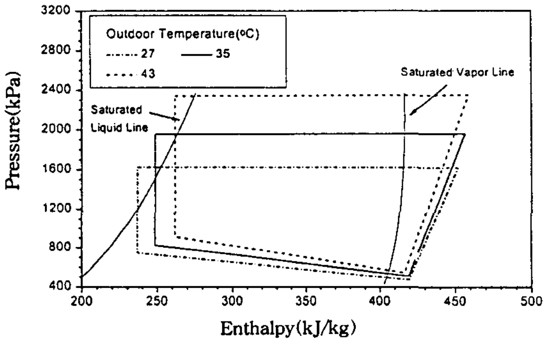

Fig.6 Pressure-enthalpy diagram with a variation of outdoor temperature at 60Hz

According to the increase of outdoor temperature, both condensing pressure and mass flow rate increased. Even though the mass flow rate increased, the cooling capacity of the system decreased due to deminishment of the enthalpy difference between evaporator inlet and outlet which was induced by an increment of condensing pressure and lowering subcooling as well. When the outdoor temperature changed from 27℃db, 24℃wb to 43℃db, 25.5℃wb, cooling capacity decreased by 11.2% from 4,226.2W to 3,751.7W, while power consumption increased by 31.2% from 1,345.2W to 1,765.3W Consequently EER was decreased from 3.14 to 2.13, by 32.2%.

Table 2 shows the results of performance test of the inverter heat pump as a function of indoor and outdoor temperature with varying capillary length at 60Hz. When the outdoor temperature increased from 35℃db, 24℃wb to 43℃db, 25.5℃wb, at a given indoor temperature of 27℃db, 19.5℃wb, both cooling capacity and EER of the system with the capillary

Table 2 Experimental results of the inverter heat pump as a function of indoor and outdoor temperature at 60Hz

Capillary Length	Item	Indoor : 27℃db, 19.5℃wb Outdoor : 35℃db, 24℃wb	Indoor : 27℃db, 19.5℃wb Outdoor : 43℃db, 25.5℃wb	Indoor : 21℃db, 15.5℃wb Outdoor : 35℃db, 24℃wb
1,000mm	Capacity(W)	4,129.9	3,751.7	3,564.7
	EER	2.7	2.13	2.36
	Flow Rate(kg/h)	102.08	105.87	97.87
	Subcooling(℃)	10.86	9.04	9.26
	Superheat(℃)	13.95	9.13	3.97
950mm	Capacity(W)	4,078.9	3,602.8	3,480.9
	EER	2.6	2.04	2.31
	Flow Rate(kg/h)	107.61	111.08	102.03
	Subcooling(℃)	9.36	6.80	6.98
	Superheat(℃)	4.31	3.24	2.87

tube length 950mm decreased compared with the case of capillary tube length of 1,000mm. When the indoor temperature decreased from 27℃db, 19.5℃wb to 21℃db, 15.5℃wb, both cooling capacity and EER of the system with the capillary tube length of 950mm decreased compared with the case of capillary tube length of 1,000mm. Consequently, the performance of an inverter heat pump system with the standard capillary tube which has the maximum EER at 60Hz and ASHRAE test condition "A" was higher than the case of reduced capillary tube length with a variation of indoor or outdoor temperature.

3.2 The performance characteristics of an inverter heat pump as a function of frequency

Before the performance test of an inverter heat pump as a function of frequency, preliminary test was executed to find optimum refrigerant flow rate, which shows the maximum EER at each frequency. Preliminary test was performed using a micro expansion valve. Optimum capillary tube size with which the inverter heat pump represented an optimum cycle was calculated using a capillary simulation program[9] with the optimum refrigerant flow rate obtained from preliminary test.

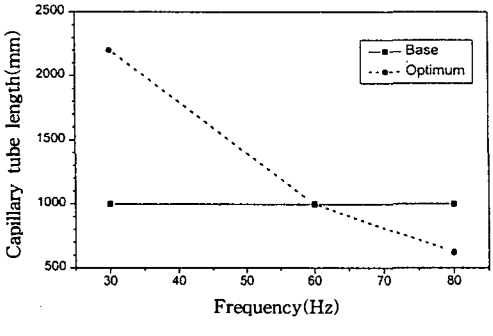

Fig.7 Optimum capillary tube length as a function of frequency

Figure 7 shows the length of optimum and standard capillary tube as a function of frequency. Optimum capillary tube length is longer than the standard capillary tube length at the low frequency level, whereas it is shorter at the high frequency level. Figure 8 represents cycle variation of the system with the standard capillary tube as a function of frequency. Figure 9 shows cases with the optimum capillary tube as a function of frequency. Applying the optimum capillary tube to the inverter heat pump at the low frequency (30Hz), the evaporator temperature slightly decreased, but condenser pressure, superheat and subcooling increased as compared with

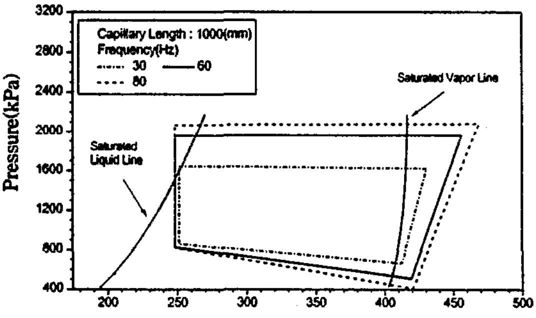

Fig.8 Cycle variation as a function of frequency applying the standard capillary

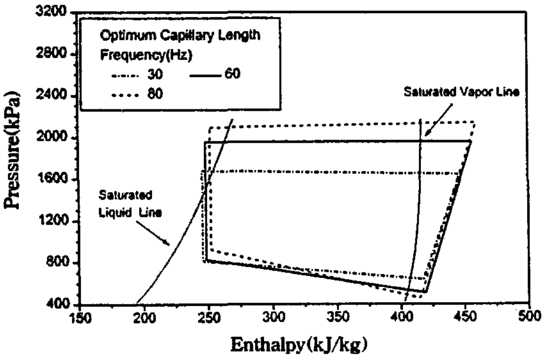

Fig.9 Cycle variation as a function of frequency applying the optimum capillary

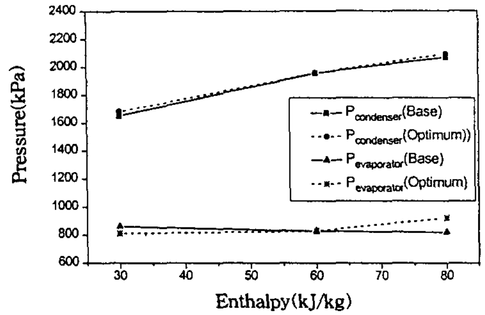

Fig.10 Variation of condenser and evaporator pressure as a function of frequency

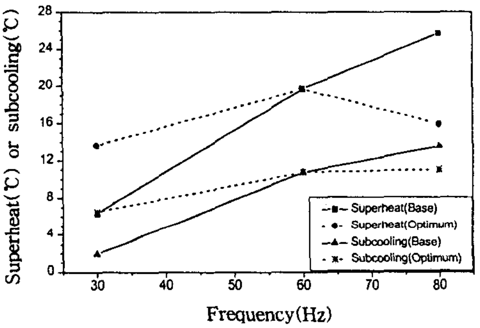

Fig.11 Levels of superheat and subcooling as a function of frequency

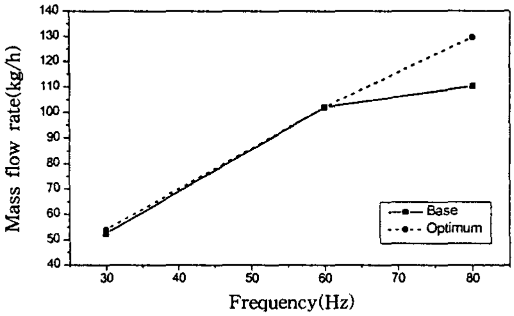

Fig.12 Variation of mass flow rate as a function of frequency

those of the standard capillary tube(Figs.10 and 11). The system with the optimum capillary showed higher flow rate than the system with the standard capillary at the low frequency(Fig.12). Enthalpy difference between inlet and outlet of the evaporator increased because of the increase of inlet subcooling of the expansion device and evaporator outlet superheat as well. As a result, the cooling capacity of the system with the optimum capillary tube was enhanced as compared with the system having the standard capillary tube. When the capillary tube length increased from 1,000mm to 2,200mm at the low frequency and ASHRAE test condition "A", power consumption of the system increased 1.5%, from 850.1W to 863.1W and cooling capacity increased 6.9%, from 2,322W to 2,483W. Consequently, EER was enhanced by 5.1%(Figs.13 and 14).

As shown in Figs 10 and 11, applying the optimum capillary tube to the system at the high frequency level, the evaporator pressure and condenser pressure increased, while superheat and subcooling decreased as compared with those of applying the standard capillary tube. The resistance of the optimum capillary tube is lower than that of the standard capillary due to the shorter length. Since condenser pressure increased and the resistance of capillary tube decreased, the system with the optimum capillary tube showed higher flow rate than that with the standard capillary tube at high frequency level. When the capillary length decreased from 1,000mm to 620mm, the refrigerant flow rate increased from 110.2kg/h to 129.5kg/h(by 17.5%). Enthalpy difference between inlet and outlet of evaporator decreased because of the decrease a superheat of evaporator outlet and subcooling of capillary tube inlet. As a result, cooling capacity of the system increased(Fig.13). When the capillary tube length decreased from 1,000mm to 620mm at high frequency level and ASHRAE test condition "A", power consumption increased from 2,117.2W to 2,202.6W (by 4%), and cooling capacity increased from 4,478.1W to 4,809.2W(by 7.4%). Consequently,

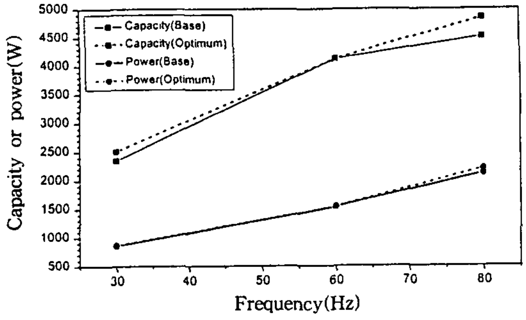

Fig.13 Variation of capacity and power input as a function of frequency

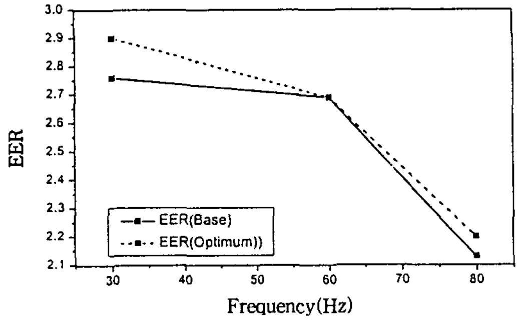

Fig.14 Variation of EER as a function of frequency

EER increased by 2.8% from 2.12 to 2.18 (Figs.13 and 14).

As the frequency was increased from low to high, the cooling capacity and power consumption of the inverter heat pump increased while EER decreased in all cases of optimum and standard capillary tubes. Since condenser pressure, degree of superheat and refrigerant flow rate increased as frequency increased, power consumption of the compressor increased (Figs.10 and 11). The increment of refrigerant flow rate and enthalpy difference across evaporator increased cooling capacity. However, the increase of power consumption with the increased frequency was greater than the increase of cooling capacity. As a result, EER decreased due to the increase of frequency.

Based on the test results of the inverter heat pump with a capillary tube, following results were obtained. Inverter heat pump can not operated optimally at all frequency levels because it is impossible for heat pump to change the capillary size which was installed in the system. For high frequency level, the inverter heat pump showed maximum performance when the capillary length decreased as compared with the standard capillary tube. Whereas, for low frequency level, the inverter heat pump showed the maximum performance when the resistance of the refrigerant flow increased by increasing the capillary tube length. For optimal operation of the inverter heat pump with a capillary tube, the refrigerant flow rate need to be reduced by increasing the resistance of the capillary at low frequency level, and it should be increased by reducing the resistance of the capillary at high frequency level compared with the standard capillary. If newly developed expansion device makes optimal cycle at all frequency levels, the seasonal energy efficiency ratio of the inverter heat pump will be significantly increased.

4. Conclusions

In this study, a standard capillary tube showing maximum performance at the rated frequency(60Hz) was chosen. Performance characteristics of an inverter heat pump were measured and analyzed according to variations of frequency, indoor temperature, outdoor temperature, and capillary tube length. The following conclusions were derived.

1) The performance of the inverter heat pump system with the standard capillary tube, which has the maximum EER at 60Hz and ASHRAE test condition "A", was higher than the case of reduced capillary tube length with

a variation of indoor or outdoor temperature.

2) As the frequency was increased from low to high, cooling capacity and power consumption of the inverter heat pump increased while EER decreased in all cases, of optimum and standard capillary tube.

3) Even though a capillary tube was selected to perform optimum performance at the rated frequency, the inverter heat pump with a capillary tube was not able to represent the optimal performance at all frequencies. For optimal operation of the inverter heat pump at all frequencies, the length of capillary must be shorter than the standard capillary at high frequency, but longer than one at low frequency level.

4) For an improvement of performance of the inverter heat pump when operating optimally at all frequencies, an expansion device, which has large resistance at low frequency level and small resistance at high frequency level as compared with a capillary tube, is in demand.

Acknowledgement

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