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A Modeling Study on the Operational Stability of a Variable Speed Direct Expansion Air Conditioning System

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A modeling study on the operational stability of a variable speed direct expansion air conditioning system

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ABSTRACT

This paper reports on a modeling study on the operational stability of an electronic expansion valve (EEV) controlled variable speed (VS) direct expansion (DX) air conditioning (A/C) system. An existing detailed, physical based dynamic model for a VS DX A/C system was further developed by adding equations for EEV's temperature sensor. Using this further developed model, a modeling study on the stability of a VS DX A/C system based on the classical minimal-stable-signal (MSS) theory was carried out. The influences of the dynamics of EEV's temperature sensor and the variable speed operation on the operational stability of the VS DX A/C system were investigated. The modelling results suggested that slowing down the rate of degree of superheat (DS) signal transfer would help mitigate the instability, while increasing the compressor speed or decreasing the supply fan speed would cause the movement of a mixture-vapor transition point towards evaporator exit, leading to potential instability of the VS DX A/C system.

Key words: operational stability; sensor dynamics; variable speed; hunting; EEV.

1. INTRODUCTION

The instability in a refrigeration system, conventionally known as hunting, is the phenomena of the oscillation of certain system operational parameters such as the degree of refrigerant superheat (DS), refrigerant mass flow rate and evaporating pressure. Hunting has been noticed in not only the refrigeration systems controlled by thermostatic expansion valves (TEVs) (Eames et al., 2014; Huang et al., 2014; Wedekind, 1971; Wedekind and Stoecker, 1968; Yasuda et al., 1983), but also those controlled by electronic expansion valves (EEVs) (Chen et al., 2008; Fallahsohi et al., 2010; Li et al., 2004; Qi et al., 2010). Hunting leads to a lower operating safety and a higher energy consumption (Liang et al., 2010), and therefore, should be avoided as far as possible for the safe and energy efficient operation of a refrigeration system.

The causes of unstable system operation have been explained by two different views. The first concentrated on the influence of the control characteristics of an expansion valve on system stability. A number of related modeling studies suggested that either increasing or decreasing the time constant of a TEV's sensing bulb would reduce the hunting of DS (Broersen and Vanderjagt, 1980; Ibrahim, 1998; Mithraratne et al., 2000). However, the second tried to explain the cause of hunting based on the inherent characteristics of an evaporator. The theory of minimal-stable-signal (MSS), defined as a critical minimal DS at which a refrigeration system could exhibit unstable operation as a mixture–vapor transition point moving toward evaporator exit, was proposed by Huelle (1967).

In general, there are more studies on the operational stability for TEV-controlled refrigeration systems than that for EEV-controlled systems. For a TEV-controlled system, it was previously shown that the time constant of TEV's sensing bulb did influence the system operational stability (Broersen and Vanderjagt, 1980; Ibrahim, 1998; Mithraratne et al., 2000), because it affected the rate of DS signal transfer. Similarly, for an EEV-controlled refrigeration system, the influences of the dynamics of EEV's temperature sensor on the DS signal transfer should also be considered. Furthermore, those reported studies were mainly based on water chillers, and therefore the influences of water side operating characteristics on the operational instability were investigated (Ibrahim, 1998; Mithraratne et al., 2000; Tahat et al., 2001). No previously studies on the influence of the air side operating characteristics on the operational stability in air coolers, most of DX type, may be identified. As a matter of fact, nowadays, variable speed compressors and supply fans are extensively used in DX A/C systems, and it was possible to vary compressor and supply fan speeds simultaneously for controlling both indoor air temperatures and relative humidity (RH) by outputting different sensible and latent cooling capacities (Li and Deng, 2007a; Li et al., 2015a; Li et al., 2015b), at different speed combinations of compressor and supply fan. Therefore, on the air side of a DX evaporator, or cooling coil, different air flow rates and wetness of coil surface will be resulted in, significantly affecting the air side heat transfer, and thus the overall heat transfer characteristics, leading to the possible change in refrigerant mass flow rate entering the evaporator. Consequently, it can be expected that the operational stability in a variable speed (VS) DX A/C system can be also affected by its variable speed operation.

In this paper, a modelling study on the influences of the dynamics of EEV's temperature sensor and the variable speed operating parameters on the operational stability of an EEV-controlled VS DX A/C system is reported. Firstly, the further development of an existing physical dynamic model for an EEV-controlled VS DX A/C system (Chen and Deng, 2006) by adding the equations for the EEV's temperature sensor for the purpose of the current study is reported. Secondly, using the further developed model, the effects of the dynamic characteristics of EEV's temperature sensor and the variable speed operating parameters on the operational stability of the VS DX A/C system were numerically studied. Thirdly the modelling results and their related analysis are presented.

2. FURTHER DEVELOPMENT OF AN EXISTING DYNAMIC MODEL FOR A VS DX A/C SYSTEM

2.1 Description of the Modelled VS DX A/C System

As shown in Figure 1, the modelled VS DX A/C system was composed of two parts, i.e., a DX refrigeration plant (refrigerant side) and an air distribution sub-system (air side). The major components in the DX refrigeration plant included a variable speed compressor, an EEV, a DX evaporator and an air-cooled condenser. The air-distribution sub-system included an air-distribution ductwork with return air dampers, a variable speed centrifugal supply fan, and a conditioned space. Inside the space, there were sensible heat and moisture load generating units (LGUs) for simulating the space cooling load.

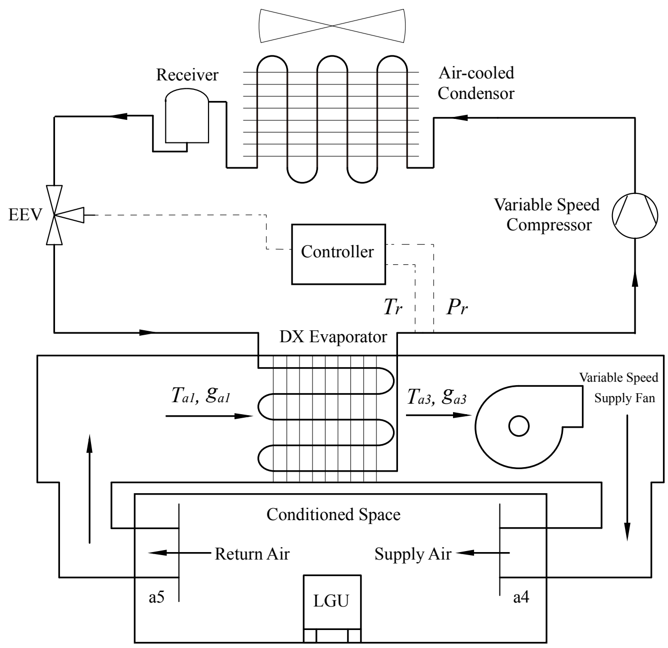

Figure 1: Schematic diagram of the modelled VS DX A/C system

2.2 Further Development of an Existing Model of the VS DX A/C System

A dynamic mathematical model for the VS DX A/C system was previously developed (Chen and Deng, 2006). However, in this DX A/C model, the dynamics of EEV's temperature sensor were not considered when modelling its EEV. For the purpose of the current modelling study, the model was further developed with respect to its EEV sub-model.

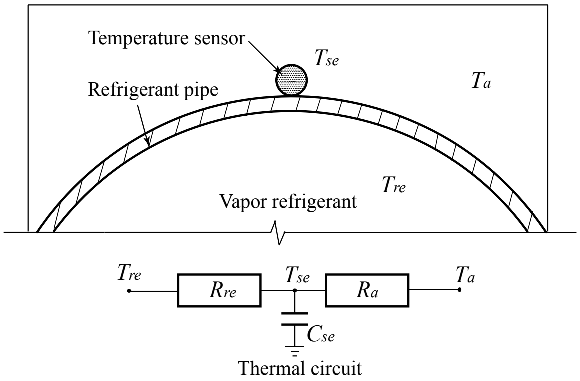

Figure 2: Schematic diagram of the installation of an EEV temperature sensor attached to the refrigerant pipeline at evaporator exit and its equivalent thermal circuits

For an EEV-controlled refrigeration system, the DS as a control signal could be evaluated by using the refrigerant temperature leaving the evaporator and the evaporating pressure measured, by a temperature sensor and a pressure transducer, respectively. Generally, the temperature sensor is clamped to the refrigerant pipeline at evaporator exit, while the pressure transducer is directly connected to the outlet pipeline of the evaporator. For a pressure transducer, the time lag of the pressure signal transfer may be negligible because pressure wave travels at the speed of sound in tubes. Therefore, the time lag of measuring DS as the feedback signal to control the refrigerant flow entering the evaporator is caused by the dynamic characteristics of its EEV's temperature sensor.

Figure 2 shows the installation details of EEV's temperature sensor attached to the refrigerant pipeline at evaporator exit and an equivalent thermal circuit for the heat transfer from refrigerant to the sensor. The heat transfer between the temperature sensor and the refrigerant inside the pipeline yielded:

$$(\rho C_p V)_{se}\frac{dT_{se}(t)}{dt}=\frac{(T_{re}(t)-T_{se}(t))}{R_{re}}+\frac{(T_a(t)-T_{se}(t))}{R_a} \tag{1}$$

where T_{re} is the temperature of vapor refrigerant at evaporator exit, T_a the ambient temperature, T_{se} the temperature measured by the sensor. R_{re} is total thermal resistance between the vapor refrigerant and temperature sensor. R_a is the convective thermal resistance between the sensor and its surroundings.

Generally, in refrigeration systems, EEV's temperature sensors and the refrigerant pipe at evaporator exit are thermally insulated to reduce heat loss. Therefore, the natural convection heat transfer between the sensor and its surroundings can be neglected. Thus, equation (1) can be simplified to:

$$\frac{dT_{se}(t)}{dt}+\frac{1}{\tau_{se}}T_{se}(t)=\frac{1}{\tau_{se}}T_{re}(t) \tag{2}$$

$$\tau_{se}=R_{re}(\rho C_p V)_{se} \tag{3}$$

where τ_{se} is the time constant of the temperature sensor, which is affected by the thermal resistance between the sensor and vapor refrigerant inside the pipe, as well as the heat capacity of the temperature sensor itself.

3. MODELING STUDY ON THE OPERATIONAL STABILITY OF THE VS DX A/C SYSTEM

The existing model has been further developed by adding equations (1) – (3) and using the further developed model a modelling study has been carried out for the influences of the dynamics of EEV's temperature sensor and the variable speed operation on the operational stability of an EEV-controlled VS DX A/C system and the study results are reported in this section. In the simulation results presented in this section, when the DS fluctuated around its setting with a magnitude over ±0.5 °C, the DX A/C system was regarded as unstable.

3.1 The Influences of Dynamic Characteristics of EEV's Temperature Sensor on the System Operational Stability

As mentioned in Section 2.2, the dynamics of EEV's temperature sensor, as reflected by its time constant, were determined by the thermal resistance between the sensor and vapor refrigerant inside the pipe, as well as the heat capacity of the sensor itself. Hence, for the temperature sensor listed in Table 1, four different cases of thermal contact resistances are given in Table 2 to examine their influences on the operational stability. In simulations, the DS setting was fixed at 6 °C, the proportional gain, K_p, and integral time, T_i, for the PI controller for the EEV were -8 and 100s, respectively. The inlet air temperature and relative humidity to the DX A/C system were maintained as 26 °C and 50%.

Table 1: Specifications of EEV's temperature sensor used in the simulation

Sensor diameter (mm)	Sensor length (mm)	Heat capacity of the sheath wall (J K^{-1})	Heat capacity of the sensor matrix (J K^{-1})
4	30	1.79	2.23

Table 2: Four cases of different unit thermal contact resistances

Study group	Study case	Thermal contact resistance R_2' (m^2 K kW^{-1})	Compressor speed (rpm)	Supply fan speed (rpm)
I	1	0.050	5544	2448
	2	0.075		
	3	0.125		
	4	0.200		

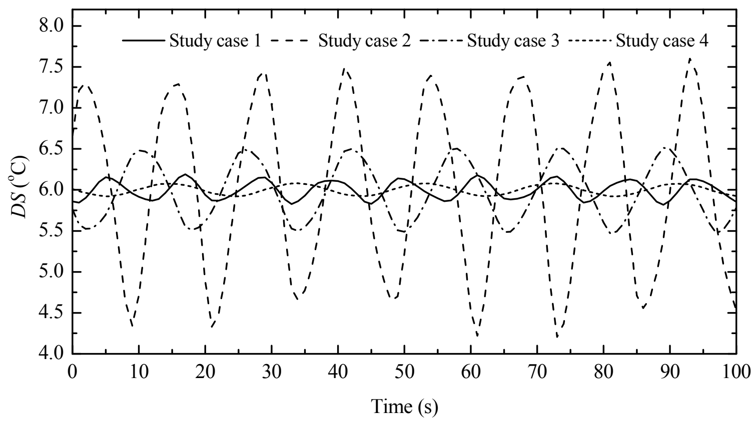

Figure 3: The simulated *DS* for study group I

The simulation results of *DS* for the four cases are shown in Figure 3. As seen, when the contact resistance, R_2', was increased from 0.050 to 0.075 m^2 K^{-1} kW^{-1}, the oscillation amplitude for *DS* was increased, suggesting an increasingly unstable operation of the system. However, when R_2' was further increased to 0.20 m^2·K kW^{-1}, the oscillation amplitude was diminished to only 0.2 ^{o}C, suggesting a stable operation of the system. Considering the fact that different thermal resistances only influenced the rate of DS signal transfer in its DS control loop, slowing the rate of DS signal, therefore, may help mitigate hunting of the system.

3.2 The Influences of the Variable Speed Operation on the System Operational Stability

In order to examine the influences of variable speed operation on stability, three groups of different variable speed operating parameters shown in Table 3, were set. K_p, T_i and R_2' were equal to -8, 100s and 0.20 m^2·K kW^{-1}, and the inlet air temperature and relative humidity were maintained at 26^{o}C and 50%, respectively, when carrying out simulation

Table 3: Three study groups of different variable speed operating parameters

Study group	Study case	Compressor speed (rpm)	Supply fan speed (rpm)	DS setting (^{o}C)
III	5	4488	2160	6
	6			5
	7			4.5
IV	8	4488	2160	6
	9	5016		
	10	6072		
V	11	4488	2160	6
	12		2064	
	13		1968	

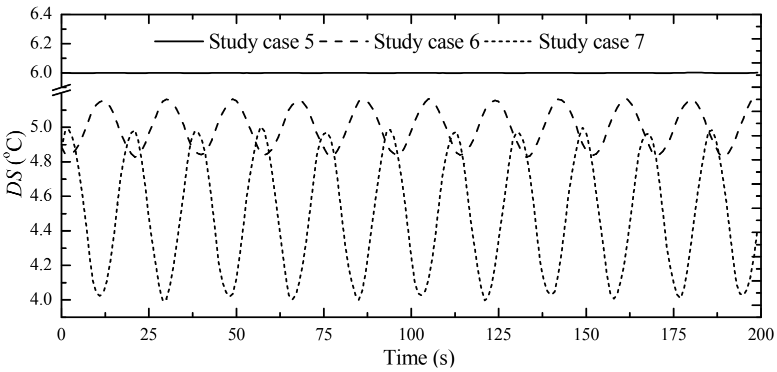

Figure 4: The simulated *DS* in study group III

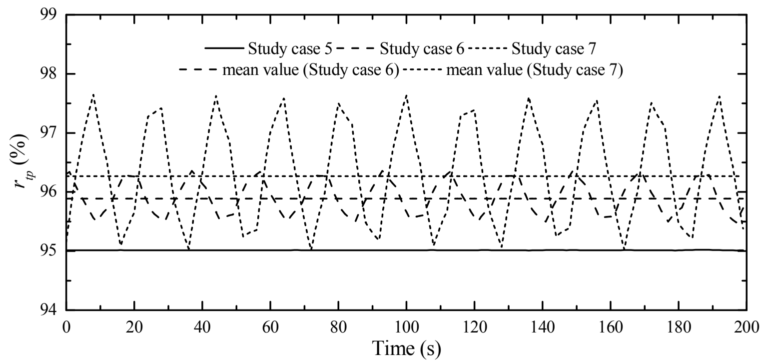

Figure 5: The simulated r_{tp} in study group III

3.2.1 Simulation results for study group III: The simulation results of *DS* in group III are shown in Figure 4. As seen in Figure 4, the oscillation of *DS* occurred when its setting was decreased from 6 ºC to 5 ºC. When the DS setting was further decreased to 4.5 ºC, its variation amplitude was further increased to 0.5 ºC, which can be regarded as hunting of the system. On the other hand, as shown in Figure 5, the simulated ratio of the length of the two-phase region to the total length of the evaporator, r_{tp}, was also increased. This can be understood that a smaller DS setting led to a shorter length of superheated region, causing the mixture-vapor transition point to move near to evaporator exit. The simulation results also validated the view of the classical MSS line theory (Huelle, 1972; Huelle, 1967) that, at decreased DS, the mixture-vapor transition point would move to evaporator exit, causing system hunting.

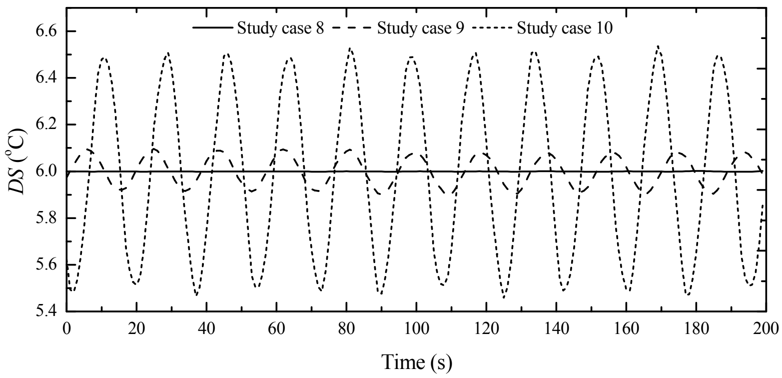

Figure 6: The simulated *DS* in study group IV

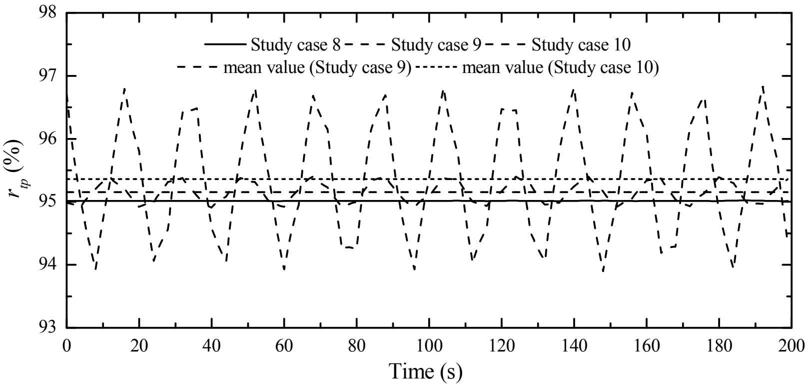

Figure 7: The simulated r_{tp} in study group IV

3.2.2 Simulation results for study group IV: Figures 6 and 7 show the simulation results for study group IV on the influences of different compressor speeds on operational stability. As seen in Figure 6, the system was stable when the compressor speed was at 4488 rpm. However, when the compressor speed was further increased to 5016 rpm, *DS* started to oscillate. When the compressor speed was further increased to 6072 rpm, system hunting occurred since *DS* fluctuated around its setting with a magnitude of over ±0.5ºC. This can be explained by analyzing the simulation results for r_{tp} shown in **Figure 7**. As seen, at a specified supply fan speed, the influence of increasing compressor speed on r_{tp} was similar to that of decreasing the DS settings, both causing the movement of the mixture-vapor transient point towards evaporator exit. This was due to that more refrigerant would be supplied to the evaporator as compressor speed was increased, but the potential cooling capacity provided by the increased refrigerant could not be fully taken away on the air side of the evaporator since the supply fan speed was unchanged, thus leading to the excess of liquid refrigerant in the evaporator, as reflected by a larger r_{tp}. Therefore, at a given supply fan speed, increasing compressor speed may cause system instability.

3.2.3 Simulation results for study group V: Figures 8 and 9 show the simulation results for study group V. In contrast to the influence of compressor speed on the system operational stability, *DS* would be more likely to oscillate at a lower supply fan speed. As shown in Figure 8, *DS* started to oscillate as the supply fan speed was decreased from 2160 rpm to 2064 rpm, and the oscillation amplitude would be further increased to over ±0.5°C when the supply fan speed was decreased to 1968 rpm. Furthermore, as shown in Figure 9, decreasing supply fan speed would also cause an increase in r_{tp}, leading to the movement of mixture-vapor transition point towards evaporator exit. This may be explained that for a given compressor speed, the potential cooling capacity provided could not be fully taken away on the air side of the evaporator when supply fan speed was decreased, leading to the less evaporation of liquid refrigerant. Although this would cause a decrease in EEV's opening to reduce the refrigerant flow entering the evaporator, there would be a surplus in refrigerant supplied for the DX evaporator, causing the flooding of the evaporator. Therefore, at a fixed compressor speed, it would become more liable to hunting for the VS DX A/C system at a lower supply fan speed.

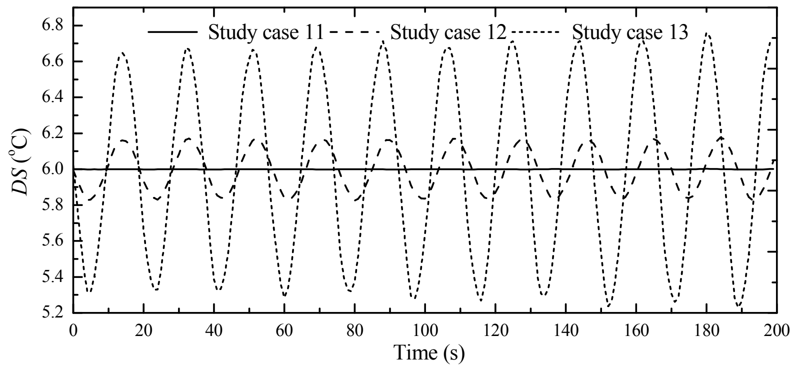

Figure 8: The simulated *DS* in study group V

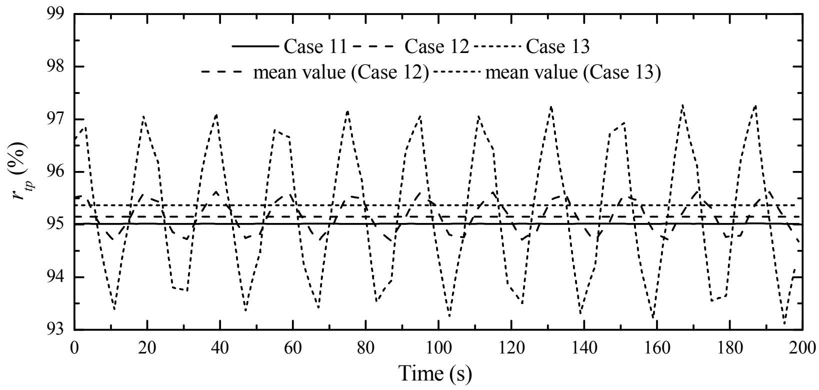

Figure 9: The simulated r_{tp} in study group V

4. DISCUSSIONS

As mentioned earlier in Introduction, there have been two views on the causes for the hunting in a refrigeration system. The simulation study reported in this paper further developed these two views on the operational stability of a refrigeration system in the following two aspects:

- The operating characteristics of an EEV did impact the operational stability for the VS DX A/C system.
- The simulation results presented in Section 3.2 confirmed that the inherent operating characteristics of the DX evaporator under variable speed operation for the VS DX A/C system impacted the operational stability. A faster compressor speed or a slower supply fan speed would lead to the movement of the mixture-vapor point towards evaporator exit, which, according to the classical MSS line theory, would lead to system hunting

5. CONCLUSION

In this paper, an existing dynamic VS DX A/C model was further developed by adding the equations for EEV's temperature sensor. A modeling study was therefore carried out using this further developed model to investigate the influences of dynamics of EEV's temperature sensor and variable speed operation on the stability of the VS DX A/C system. The simulation results shown that slowing down the rate of DS signal transfer by increasing the thermal resistance between the sensor and refrigerant inside the pipeline may help mitigate the instability. Furthermore, a higher compressor speed or a lower supply fan speed would cause the movement of mixture-vapor point towards evaporator exit, leading to likely system hunting.

NOMENCLATURE

T	temperature	(°C)
C_p	specific heat	(kJ kg^{-1}·K^{-1})
K_p	proportional gain	(–)
Ti	integral time	(–)
R	thermal resistance	(K kW^{-1})
R'	unit thermal resistance	(m^2 K^{-1} kW^{-1})
V	volume	(m^3)
DS	refrigerant degree of superheat	(ºC)
r	length ratio	(%)

Subscripts

re	refrigerant side
se	sensor
tp	two phase

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