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A Review of Gas Pumps Fault Behavior and Measurement, Diagnosis and Identification Methods Including Virtual Sensors

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Abstract

Almost half of all electrical pump capacity consume in three-phase induction motors and most of them use in gas pumps and compressor in processes of industries for heating, cooling, pumping, conveyors, etc. The most important role of fault detection and detection (FDD) for manufacturing equipment is an effective indicator that can identify the faulty state of a process and then take appropriate action against future failures or adverse events. The impact of proper maintenance is reflected on an especially costly type of industrial machine. To avoid reducing the efficiency of the gas station, automated fault detection and diagnostics is very important and need to study. This article aims to establish a criterion for selecting which faults can be tested under laboratory conditions or by simulation with a virtual model and to determine the features that identify those faults. This efficiency identify of faults leads to saving of energy, service and operating costs. Virtual sensors applied to gas pumps to reduce the cost associated with FDD implementation are described. Finally, several areas of improvement for the aspects reviewed have been identified: increase the use of performance indicators for FDD, new and updated studies about the health status of field heat pumps, testing methods that take into account the gradual and probabilistic nature of heat pump faults and further research in the use of virtual sensors in FDD systems.

Keywords: Fault detection, Laboratory testing, Virtual sensors, Gas pumps, Fault modeling

1. Introduction:

Heat pumps are one of the most efficient technologies for space heating and cooling and, coupled with renewable electricity sources they can reduce greenhouse emissions compared with classic solutions. However, the refrigerants used in heat pumps could have high global warming potential (GWP). These refrigerants could leak to the environment due to a leakage in the circuit or incorrect disposal at the end of life. For this reason, the restrictions to the use of refrigerants with high GWP are increasing, promoting the use of natural refrigerants, such as propane or carbon dioxide with lower GWP. Despite their high performance, heat pumps could suffer fault conditions that can affect their optimal operation and reduce their energy efficiency [1]. There is a typology of faults called “soft faults” because they reduce the equipment efficiency while still covering the demand, making them difficult to detect [2]. These faults could remain undetected for long periods, increasing the energy consumption and could worsen and damage the heat pump. Fault Detection and Diagnosis (FDD) systems are used to detect soft faults or performance decreases [3].

Automated fault detection and detection (FDD) systems have the potential to energy utility costs and reduce operating costs by lowering service. Business productivity is also improved based on the low-cost reliable sensors and low installation cost and reduction of equipment downtime. Natural gas pumping unit is a very difficult object for diagnosis. A lot of combinations of technical equipment, different operational conditions, and other factors require design and implementation of reliable diagnosis methods. Parametric diagnosis methods and techniques have been presented in papers [4], [5].

For estimating the gas pump mass flow rate three different model of virtual refrigerant mass flow (VRMF) sensors were evaluated [6].

The first model:

Uses a flow rate to measure the saturation temperature of condensation and evaporation and to measure the inlet temperature [7].

The second model:

Relatively independent of expansion valve and compressor errors that affect the mass flow rate, compressor energy balance is used with power consumption from an energy heat loss model and a virtual compressor power (VCP) sensor [8].

The third model:

Application and Development of Electronic Expansion Valves (EEV) based on an Empirical Correlation for Thermal Expansion Valves (TXV) and an Orifice Equation [9].

Braun Kim and Payne developed FDD method for a residential system with TXV. [10]. Six different faults were imposed: 1) improper indoor air flow, 2) presence of non-condensable gas, 3) compressor/reversing valve leakage, 4) refrigerant undercharge/overcharge, 5) liquid-line restriction and 6) improper outdoor air flow Li and Braun developed a FDD methodology. High-value isolated features are provided by a number of virtual sensors, using a combination of measurements and low-cost models. Virtual sensors were developed for condenser, expansion valve, compressor, evaporator and refrigerant charge. Improvement of existing sensors and extensive validation [11].

The method of fault diagnosis can be summarized by the following steps [12]:

1- Defect diagnosis: Time to detect and determine the occurrence of a defect in a system.

2- Error separation: Locate the defect.

3- Defect identification: Determining the nature of the defect and its type.

4- Error analysis: Urgency of corrective action and analysis including size (intensity).

5- Error accommodation: Modify operating conditions (process optimization) and reconfigure the system using sound components (maintenance) or based on risk analysis [13].

Defect detection methods can be classified into one of the methods FD (for error detection) or FDI (for error detection and isolation) or FDIA (for error detection, isolation, detection and analysis [14].

- Focus on reducing lifetime costs,
- Reduce costs due to reduced production.
- Reduce operating costs such as energy consumption, service and maintenance.
- Reduce costs associated with increasing longevity.
- Increase safety for humans, the environment and the vehicle.

Troubleshooting techniques are classified into two distinct groups based on the use of a mathematical model of a system [15].

1. Model less techniques (signal based).
2. Model-based techniques.

The purpose of this review is to identify common defects and features that should be considered when developing an FDD, and it is structured in several sections as follows [16]:

1. Compares different reviews on FDD at gas stations.

2. The process of validating an FDD by simulating those errors in simulation environment or a laboratory.
3. The cost of adding additional sensors the main disadvantage of applying FDD to gas pumps is improving gas pumps.

2. Methodology

The methodology adopted for this study includes the following steps [17]:

1. Study Virtual sensors and FDD simulation techniques in improving gas pumps.
2. Study of common faults on vapor compression systems and their effects.
3. Procedural errors in field studies are reviewed.
4. Review a Virtual Data collection with sensors that enables instrumentation to reduce the cost of fault detection.

In this research main area searches for keywords as error detection, search, FDD and Compression cycle were used. Classification is applied in fault diagnosis and general diagnostic methods for special HVAC equipment and gas pumps. After a thorough study, it should be noted that some topics, despite their importance in development and validation, have been superficially examined in the FDD method. Most reviews have focused on the FDD method itself [18].

2.1 Virtual Sensors

Virtual sensors development for the HVAC field has limitations such as scattered industrial nature recently, Lee and Brown developed a number of virtual sensors for compressor, expansion valve, condenser used in packaged air conditioning equipment [19]. These virtual sensors can be used to estimate power consumption and mass flow using only temperature sensors. These values can be used to determine COP and system capacity as part of a fault impact assessment. And to isolate specific faults, they can also be used in combination with other virtual sensors. Various virtual sensors were investigated for HVAC&R [20].

2.2 Virtual Sensors Benefits

•Several advantages of virtual sensors over real sensors.

1. Real sensors may not respond as quickly as needed to feedback to operators or control the process, so some values are not directly measurable due to slowness. But virtual sensors can predict sensor output without any time delay output [21].

2. To provide continuous information from time-delayed input signals, virtual sensors can be used to solve these problems by predicting sensor output using mathematical models. There may also be significant delays due to communication between reads [22].

This delay time can prevent proper response of the operator and control.

3. In very small spaces, virtual sensors have the advantage of being mounted on useful physical sensors.

4. Geometric constraints can often lead to inaccuracies in real sensors.

5. A virtual sensor can be used if during a process, a real sensor is damaged, another common application for virtual sensors.

6. The output of both virtual and real sensors can also be compared for fault detection.

7. Using virtual sensors, in addition to detecting the error, it can be restricted in the system localization and its propagation until the system is able to recover.

8. Costs are significantly reduced by using virtual sensors instead of some expensive physical sensors.

9. Some physical sensors are very expensive and need to be maintained for life

10. Physical sensors also have problems maintaining calibration due to their design.

11. Virtual sensors can encapsulate real sensor information through simpler mathematical relationships.

12. A virtual sensor reduces the learning overhead of various relationships and can increase the usability of sensor data [21-23].

2.3 Developing Virtual Sensors with two steps

Using three definitions, the general process of developing a virtual sensor can be expressed [24].

1. Basic data in this case is collected and pre-processed.

Virtual sensor models can be obtained from accurate and reliable data collection, calibrated measurements as input data for preprocessing algorithms the type and range of input data based on the modeling approach of a virtual sensor model based on steady-state performance Conditions should use transient data from measurements Filter from steady state detection algorithm [25].

2. Model training selection and selection is the main process in virtual sensor development

Sensors based on data input requirements, selected model and physical parameters

Can be specified. In most cases, the model may be trained based on the actual sensor output and the measured input data.

3. Virtual sensor can be used as a standalone sensor with its own hardware Built-in system. The software and input / output channels can then be implemented as a virtual sensor Validation based on statistical error analysis.

3. Common faults on vapor compression systems and their effects

Coefficient of operation (COP), pump power consumption, saturation temperature of condenser inlet, outlet saturation temperature, which depends on the suction line pressure, sub-cooling and heating, both of which depend on the liquid line pressure, since the effect of these defects on the gas pump type and it depends on whether the system is in heating or cooling mode, to describe the effect of defects on the variables we have used a gas pump that works in cooling mode [26].

3.1 Outdoor mechanical component failure (OMC) and outdoor unit fouling (FO)

It is usually exposed to pollution in outdoor installations. Waste and waste that can accumulate in between the internal slots of filters or pump slots or the air inlet. In addition, reducing the performance of the tail can cause damage to the pump components. The study on external unit deposition errors (FO) has not been significantly performed. Error blocking air inlet or reducing airflow. In some studies on particle deposition, the effect on the heat transfer of the coil is low and increase the air pressure drop is its main effect [27].

3.2 Failure of Indoor Mechanical Component (IMC) and fouling of indoor unit (FI):

Indoor unit fans, pumps, or controls may have mechanical faults and affect deposits and the same type of dirt on indoor pumps as outdoor units. For systems with fan coils, fan performance or duct size can also reduce airflow velocity [28].

3.3 The Valve leakage (VL):

The valve leakage error refers to a leak, and this leak is usually associated with the pump inlet and outlet valves. This valve seal can break, which in turn leads to leakage. If the drain valve is loose, the saturation temperature of the refrigerant at the condenser inlet decreases while the compressor is in the suction phase, when saturation temperature at the evaporator outlet decreases [29]. In response to an increase in saturation temperature at the evaporator outlet for heat pumps equipped with a thermostatic expansion valve (TXV), valve stimulation reduces the mass flow rate. This error affects capacity and COP and increases SHR.

3.4 Non-condensable gas (NON):

During start-up, refrigerant must be cleaned before charging, and remove moisture inside and all air. If some moisture or air remains in the system, pump does not work well. The presence of incompressible gases may cause condensation to settle, increase system pressure, reduce efficiency, and even cause TXV to malfunction. Condenser pressure increases with partial pressure of incompressible material [30]. This increases the power consumption and reduces the capacity of the compressor and is known as the error that has the greatest impact on system performance.

3.5 Compressor overcharge: CO

During commissioning, a charge higher than the pump design capacity specified by the manufacturer may be apply by the technician. This error reduces COP quantity [31]. Sometimes error levels increase the capacity of the gas pump less than 20% [32], but this may depend on the of each gas pump specific characteristics.

3.6 Compressor undercharge: CU

During start-up, if the refrigerant charge is less than what the designer specified. Any refrigerant leakage may reduce the refrigerant mass and eventually the severity of the error will increase over time, and the working point will be lost. In this situation, the refrigerant is eliminated, [33] for devices with TXV, the mass reduction effects are almost negligible when the charge level is less than 20%. Properties that are more sensitive to this error are sub-cooling and heating [34].

3.7 Liquid line restriction (LL):

To remove solid particles, the dryer and filter are installed in the liquid line, if the material is rusty due to inefficient pipe joinery or if the technician did not follow proper refrigerant charging methods, particles will enter the circuit. Refrigerant flow restriction due to waste Blocks the filter/dryer. The result is that, a decrease in refrigerant flow rate is happen, superheating process will occur in suction, and in cooling capacity a decrease will be [35]. Equipment with TXV, However, the fault effect is insignificant for error quantities below 10% [36].

3.8 Sensor error (SEN):

Sensor measurement is used to detect FDD. The accuracy of the sensors is lost due to aging [37]. For procedures for detection of drift, data mining or measurement bias, use large amounts of sensor data is important .The accuracy of the sensor affects the performance of the pump itself and the performance of the FDD. If a faulty sensor is used to control the device internally, performance will be impaired [38]. Therefore, sensors that measure FDD performance or gas pump should be monitored to ensure that data is provided correctly.

4. Procedural errors in field studies

The main source of data on field facilities are lack of information on gas pump errors due to aging in real facilities repair services. When there is a problem with the pump, these services are usually requested. And circumstances that led to the defect are never reported. While soft errors have been the main focus of the FDD literature, the cause of the problem is provided only with the repair report. Hard errors can make system impossible to reach comfortable conditions or prevent it from working and appear suddenly. Then, hard errors are easily recognizable after occurrence and are easily recognizable. On the other hand, soft errors usually permit the system to continue working but reduce performance and may worsen during the time. Soft defects are difficult to diagnose and can lead to poor repair.

4.1 Laboratory simulation environments and testing reproduced errors

Table (1) shows a set of different errors tested. They mimicked condenser deposition, evaporator deposition, leak compressor valves, fluid line limitation, and leakage of refrigerant by equipment in the laboratory. Article data, condenser deposition corresponds to the actual sample FO error. Evaporator (FI) precipitation was amplified putting paper on the filter of air. VL simulation was performed by unpacking a gas bypass line controlled by a hand valve. To increase the pressure drop, LL was performed by placing a valve in the fluid line. By removing the charge from the refrigerant circuit, Refrigerant leakage (RU) was reproduced. Incompatible gas was added to the refrigerant circuit and refrigerant charge. A constant amount of dry nitrogen was added to the refrigerant circuit, to mimic the NON error [47]. By lessening the speed of circulating pumps, reducing water flow of condenser and reducing water flow of evaporator were reproduced. Defective valves of expansion and oil of excess were also simulated.

Table (1) Summary of laboratory testing emulated faults under on real equipment [39]

Error type	Simulation technique	Quantifying	Error level	Reference
Outdoor unit fouling	Reduced of pump/fan speed	% reduced of Air flow	10 ~ 50	[40-44]
	Area of the filter blocking	% Area blocked	14 ~ 39	[45]
Outdoor mechanical component	Creating a mechanical imbalance by attaching a weight to the fan	Not defined	Not defined	[45]
Fouling of indoor unit		% reduced of air flow	40	[40]
Fouling of indoor & Failure of Indoor Mechanical Component	Reduced speed of fan/pump		5 ~ 33	[44]
Valve leakage	Open the gas bypass valve to the specified amount	% Compress reduction	8 ~ 56	[46]
Sensor error	Add a bias to the measured value of the sensor	Added temperature ◦C	- 4 to 4	[46]

4.2 Reproduced faults at virtual environments

Real tests are expensive. In some cases, the performance of the gas pump can be permanently reduced or even deactivated as a result of tested errors. Models for fault modeling and Gas pumps are increasingly used to validate FDD methods under various fault-free and defective conditions, including the occurrence of simultaneous faults [48]. Modeling Simulations can also provide further insight into generalities impact of the defects in system performance, nteraction between simultaneous errors, power consumption, and pump performance [38]. Several studies have been conducted on FDD using simulations of the gas box model modeled in the white and gray box approaches. For IMC, OMC, FO and FI errors, to simulate airflow reduction use white and gray box models while gray boxes are used only to lessen airflow in pumps, VL defect is usually simulated by lessening refrigerant mass, flow velocity and mixing effect during suction On the refrigerant, thermodynamic properties have also been considered for [49]. LL defect is simulated with additional pressure drop in the liquid line NON error accumulates only inside the condenser. In reading temperature sensors, control sensor errors in HVAC systems are often simulated by considering positive and negative offset values. Error modeling methods Used in the summary table literature. The tables show the error levels used to test and simulate the error. These levels may not represent real situations. The average reduction in airflow with sedimentation in the outdoor unit (FO) is 26%, and in the real case d is 1.3% [50, 51]. The same is true for NON faults, where fault levels in field studies do not exceed 5% .The tables also show that there is a lack of standardization of some faults, especially for FO. Attempts have been made to homogenize error simulations. Stated that errors are simulated using a definite or random approach. Fixed error simulation assumes that errors occur during the period of simulation while the random approach only considers the probability of error occurring.

Table (2) Error modeling techniques Summary for gas pumps. Definition of percent values with respect to free conditions error. Reference: fouling factor [39]

Error type	Simulation technique	Error level	Reference
RO&RU	Charge variation	70 ~ 130%	[52]
Fouling of indoor & Failure of Indoor Mechanical Component air side	Grey box: Increase the friction coefficient or decrease the fan speed to reduce the air flow speed	0 ~ 55%	
	1) UA introducing Reference modeling		[53]
	2) UA degradation modeling with degradation coefficient α		[48]
	3) Regressions drop of air pressure and on effective heat transfer of air-side		[44]
	4) UA based reduction on LMTD value changes		[53]
Liquid line restriction	Pressure drop Increasing during liquid line	0 ~ 3500%	[47]
Non-condensable gas	Relative and total pressures changes	0 ~ 20%	[49]
Valve leakage	Refrigerant mass flow reduction	0 ~ 50%	[44]
Sensor error	Effect of mixing on enthalpy of suction offset addition	±0.5 K	[48]

5. Virtual Data collection with sensors

In the development of FDD systems, a critical stage is the selection of sensors and features for analysis. Virtual sensors implementation enables instrumentation to reduce the cost of fault detection. Some studies in the literature use a significant number of measurements (in some cases almost one hundred sensors [60]) while other studies use very few (for example nonintrusive load monitoring (NILM) [47]). Most of the virtual sensors proposed for monitoring the error are based on the first and gray models of systems behavior [50]. Information are provided with these virtual sensors about system performance with indirect measurements (eg, volumetric flow velocity and pressure with virtual sensors). While others indicate the status of the system in terms of defective performance (for example, virtual sensors indicate the level of sediment).The table summarizes the types of virtual sensors and how they are made. Shows gas compression systems for performance estimation

Table (3) Models of virtual sensors in errors systems and detection of pump units [51]

Virtual sensor	Procedure	Input needed of sensors	Error level	Reference
Sensors of Pressure	Pressure drops and saturation pressures	Te, Tc	-5 ~ 9%	[52]
CP	Plan of Compressor ARI 10 coefficient polynomial	P suc, P ids	±5%	[48]
CP	Map of Compressor 6 coefficient.	Tc, Te, f	±4 ~ 8%	[49]
Frequency of Compressor	Parameter of Frequency correction	m ref	6 ~ 10% RMS	[47]
Flow rate of Air	Balance of Energy	m ref , T suc, P suc, T II, P II, T aie, T aoe, Φ aie, Φ aoe		[53]

- Compressor Power

5.1 Refrigerant charge virtual sensor

Refrigerant charge important levels are for pump performance effectively studies, it can be seen that more than 50% of the air conditioning units have a large deviation from the optimal charge as a result of insufficient start-up services and leakage [54]. The possibility of non-intrusive estimation of refrigerant mass is provided by a virtual charge sensor in the units. This gives a virtual measurement of the refrigerant mass (mtotal) by using four measurements of surface temperature (suction, compact temperature, evaporation, and liquid line), according to the following formula.

$$\frac{m_{\text{total}} - m_{\text{total, rated}}}{m_{\text{total, rated}}} = \frac{1}{k_{ch}}(T_{sc} - T_{sc.rated}) - \frac{k_{sh}}{k_{sc}}(T_{sh} - T_{sh.rated}) \qquad (1)$$

5.2 Virtual compressor mass flow meter

Mass flow rate measuring of the pump for system monitoring is useful and diagnostics, but is generally not possible. Several virtual flow sensors are used to overcome this limitation.

Total of these methods are divided into three techniques:

1) Using constructive information and polynomial regression for estimation method.

2) Balance of energy method based on the compressor plan for consumption of power.

3) Experimental correlations based on the expansion device performance.

The first one is based on the ANSI / ARI standard. For pumps with a constant speed compressor.

They present an equation for calculating the mass flow rate of refrigerant ($\dot{m}_{\text{ref}}$) with the input of evaporation saturation temperature (T_e), density saturation temperature (T_c) and density at the compressor inlet. ρ_{suc}), This equation is presented as follows:

$$\dot{m}_{\text{ref}} = \rho_{\text{suc}} (a_0 + a_1 T_c + a_2 T_c + a_3 T_e^2 + a_4 T_e^2 + a_5 T_c T_c + a_6 T_e^3 + a_7 T_e^3 \quad (2)$$

Second-order polynomial equation to obtain the rate of mass flow, when the compressor is applied at a variable speed, the pump equation is in the form of a second-order polynomial that calculates the frequency, as provided by the following expression:

$$\dot{m}_{\text{ref}} = \rho_{\text{suc}} (c_1 (f - f_{\text{rated}})^2 + c_2 (f - f_{\text{rated}}) + c_3)(b_0 + b_1 T_c + b_2 T_c + b_3 T_e^2 + b_4 T_e^2 + b_5 T_c T_c)_{\text{rated}} \quad (3)$$

Where f indicates the frequency of compressor and the named subtitle. Calculating mass flow of Cconstructive data for is based on efficiency of volumetric [54]:

$$\dot{m}_{\text{ref}} = \eta_v \frac{NV}{v_{suc}} \quad (4)$$

η_v: Yield of volumetric

V: Displacement Volume

ν_{suc}: Specific volume of refrigerant in the suction line

N: Number of suction blows per unit time

In this approach, however, there are other expressions for estimating volumetric efficiency with temperatures and discharge and suction pressures as inputs [54]. Energy balance can be applied to calculate the mass flow rate, which is valid for constant speed and variable speed compressors.

$$\dot{m}_{\mathrm{ref}} = \frac{W(1-\alpha_{\mathrm{loss}})}{h_{\mathrm{dis}}(T_{\mathrm{dis}}.P_{\mathrm{dis}})-h_{\mathrm{suc}}(T_{\mathrm{suc}}.P_{\mathrm{suc}})} \quad (5)$$

α: Losses are the ratio of the compressor heat losses.

h_{dis} (T_{dis}, P_{dis}): Enthalpies in the discharge line.

hsuc (T_{suc}, P_{suc}): Enthalpies in the suction line.

W: Power consumption of the compressor.

The third method uses operations to calculate the flow rate Principle of expansion devices to control mass flow velocity and pressure reduction. In this method, the mass flow rate is calculated using quasi-experimental models for TXV and EEV devices. In the case of TXV, an experimental model is proposed which assumes that the mass flow rate is a linear function of the area in which the valve is opened. The following equation is obtained [54].

$$\dot{m}_{\mathrm{ref}} = [a_3(P_{sat}(T_{\mathrm{suc}})^2 - P_{\mathrm{suc}})^2 + a_4(P_{\mathrm{sat}}(T_{\mathrm{suc}}) - P_{\mathrm{suc}}) + a_5]m_{\max} \quad (6)$$

The third method to calculate the flow rate to control the refrigerant mass flow rate and reduce the refrigerant pressure uses the principle of operation of expansion devices. Using this method, the mass flow rate for TXV and EEV devices is calculated using semi-empirical models. An empirical model for TXV is proposed, which is assumed that the mass flow rate is a linear function of the area value in the valve opening. And the following equation is obtained.

$$\dot{m}_{\mathrm{ref}} = [a_3(P_{sat}(T_{\mathrm{suc}})^2 - P_{\mathrm{suc}})^2 + a_4(P_{\mathrm{sat}}(T_{\mathrm{suc}}) - P_{\mathrm{suc}}) + a_5]m_{\max} \quad (7)$$

$m_{\max}$: mass flow rate of refrigerant for the expansion device in full open position.

P_{sat} (T_{suc}): saturation pressure for the temperature of the suction line.

The maximum flow rate depends on parameters such as valve pressure drop and orifice size and can be determined experimentally [56].

6. Conclusion and perspective on future research

In this study investigates the behavior of defective pumps in field and laboratory

Research, along with cognitive methodology considerations including instrumentation

With virtual sensors and techniques of simulation for FDD Models.

Methods for sensor requirements have been evaluated,

Types of errors and error levels with new contributions:

- Newly reported performance rankings of different FDDs were compared
- The effects on heat capacity and COP and pump defects were explained and collected in the table
- The simulations were presented in order of useful feature description for FDD.
- Virtual sensors for FDD are described and tested

More progress can be achieved with more detailed analyzes in different areas and the following items can be considered for future work:

- The methods used to reproduce fault treatment in simulations and experimental tests are not representative of the actual occurrence and level of faults and studies are not homogeneous in terms of the fault levels and methodologies they use. New methods that are more representative of realistic conditions need to be developed to account for the gradual generation and probabilistic nature of fault behavior in heat pumps.
- Virtual sensors are cost-efficient but, to date, they have been used only in a limited number of FDD research. Further study is needed to analyze the performance of fault diagnosis systems that apply these alternative sensors and to identify potential limitations and areas of improvement.

7. Parameters of virtual sensor

VCP sensor

- $\dot{W}_{VCP}[\%] = \frac{(k_0+k_1T_c+k_2T_c+T_e^2+k_4T_e^2+k_5T_c\cdot T_c+k_6T_e^3+k_7T_e^3+k_8T_e^2\cdot T_c+k_9T_c^2\cdot T_e)}{\text{rated compressor power (system specification)}}$ (8)

VCP sensor parameters									
k_0	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9
−17995	84.097	0.161	16208.658	489.2354	2.417	553.322	−2.334	−3.546	0.021

VRMF sensor

$$\dot{W}_{\text{VRMFI}}\,[\%] = \frac{\rho_{\text{suction}}\cdot(f_0+f_1T_c+f_2T_c+f_3T_e^2+f_4T_e^2+f_5T_c\cdot T_c+f_6T_e^3+f_7T_e^3+f_8T_e^2\cdot T_c+f_9T_c^2\cdot T_e)}{\text{rated refrigerant mass flow rate}} \quad (9)$$

VCP sensor parameters									
f_0	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9
−161.41	4.037	−0.032	−355.37	14.327	0.106	2.031	0.031	0.363	0.074

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