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Heat Transfer Analysis inside the Hermetic Reciprocating Compressor: A Review

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---*ABSTRACT*---
To design a highly efficient hermetic reciprocating compressor for HVAC applications, understanding of thermal behavior of compressor is necessary. The compact structure and airtight assembly of compressor components make the system complex. The major inadequacy linked with the compressor is overheating, that is, a rise in refrigerant temperature before entering the compression chamber. To avoid overheating, understanding of thermal interactions inside the different components of a compressor is necessary. This paper presents a short review of methods of heat transfer analysis and various techniques used by researchers worldwide to study the thermal behavior of the compressor. The objective of this paper is to put forth currently used techniques of heat transfer analysis. A brief description of the method, its methodology, and work in literature based on that method is presented. The pros, cons, and application areas of each technique are also discussed in brief. Each method has its application area and differs from other methods in accuracy and complexity.

KEYWORDS;-*Hermetic Compressor, Reciprocating compressor, Heat transfer***,** *Thermal analysis, Review*

I. INTRODUCTION

Today Refrigeration and air conditioning cover almost every field of application such as food conservation, climate control, space, aircraft and military application, etc. The demand for refrigeration equipment is increasing day by day. Nearly 20% of total residential electricity consumption in India is by refrigerators and air conditioners [1]. The refrigeration can be achieved by various means, among which mechanical vapor compression refrigeration system (VCRS) is employed in all domestic, commercial and industrial refrigeration systems as well as in automotive climate control systems [2]. The major components of VCRS are Compressor, Condenser, Expansion Valve, and Evaporator. In which, the compressor plays a key role in energy consumption. The compressor is the heart of the refrigeration system. The thermodynamic performance of compressors is considerably affected by the overheating of the suction refrigerant.The refrigerant gets overheated as it comes in contact with hot components of the suction system and hot cylinder wall. The overhearing affects the system, as the volumetric efficiency of compressor decreases due to density variation with temperature. According to Gosney, [3] some superheating is needed for the proper operation of a compressor because it ensures the elimination of non-evaporated coolant drops at the evaporator outlet. This ensures that the fluid refrigerant entering the compression chamber is fully in the form of vapor, avoiding water hammer.

In order to study overheating and to reduce its effect, one should know the distribution of temperature inside the compressor. But, the prediction of temperature is not an easy task because of the complex nature of heat transfer inside the compressor.

II. HEAT TRANSFER ANALYSIS

1. Experimental Methods

Measurements of temperature are widely used in the development of refrigeration compressors to identify and eliminate phenomena that unnecessarily increase the gas overheating in suction. Besides, experimental data are also important for the calibration and validation of simulation models.

In this method, heat transfer inside the compressor is analysed by means of temperature measurement using temperature transducers such as thermocouples, RTD, etc. The thermocouples are placed inside the compressor or on the surface of the shell to measure the temperature. The temperature measurement helps in the energy balance of different compressor components by evaluating enthalpy values at the inlet and exit of components. From enthalpy values, it is easy to evaluate the advective energy transfer.

$$Q = m\,(H_i - H_o) \quad (1)$$

Once the **Q** is calculated, the overall heat transfer coefficient (**U**) can be easily calculated from equation 2,

$$Q = UA(T_g - T_s) \quad (2)$$

It is possible to knowthe hot and cold sources in the compressor by using a measurement of temperature. This helps in identifying components responsible for the overheating process.

Work in Literature:

Meyer and Thompson [4] and Kim et al. [5] used thermocouples for temperature measurement. The overheating of suction gas due to contact with warmer components such as shell, motor, and cylinder head, etc. is evaluated by measurement of refrigerant temperature inside the compressor by placing thermocouples on different components of the compressor.

References [6-8] also did temperature measurement using thermocouple in different regions of the compressor for validation of their simulation models. The thermocouple wires were placed at different locations of the compressor. Fig.1a shows the thermocouples on the inner parts of the compressor while fig.1b shows shell temperature measurement on the shell.

This method of heat transfer evaluation allows the evaluation of the flow in several regions and the determination of global conductance coefficients UA through energy balances. Finding these coefficients is necessary for the solution of some integrated simulation models, such as those proposed by [9] and [10].

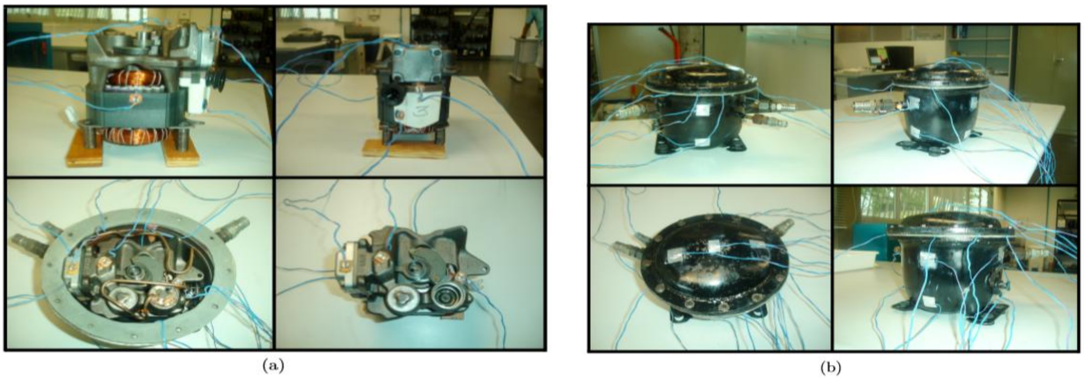
(a) (b)

Fig 1: Thermocouple arrangement for temperature measurements

The work in the literature using the experimental method is vast and few referred material is summarized in Table 1.

Table 1: Experimental methods literature work summary.

AUTHOR	YEAR	TOOL	PURPOSE
Meyer &Thompson Kim et. al.	1999 2000	• Thermocouple	Study of overheating
Cavillini et. al. Ooi Pizzaro	1996 2003 2006	• Thermocouple	Evaluation of Thermal Conductance &Validation of a Simulation model
Adair et. al.	1972	• Fast Response Thermocouples	Heat Flux calculation and Evaluation & modification of correlations
Thiago Dutra	2008	• Heat Flux sensors • Infrared Thermography	Calculation of Heat transfer rate and temperature distribution
Morriensen	2009	• Cold wire sensor	Heat Transfer Analysis
Dincer et.al.	2015	• Pressure Transducer • Optical Encoder	Time dependant pressure-volume diagram.
Guo et. al.	2018	• T Type Thermocouple • Pressure Sensors	Experimental Validation of numerical study

This method of heat transfer analysis provides accurate and precise results even for complex geometry. This is a promising method for the validation of results obtained from numerical methods. Advanced techniques of measurement make this method even more reliable. The main drawback is that it requires high operation costs.

2. Numerical methods

With the development of computers and numerical methods, the use of numerical techniques in the field of compressor analysis is increasing. These methods are used to predict temperature distribution inside the compressor for various operating conditions. These models are classified according to discretization techniques, complexity, and computational time in three categories:

A. Integration Method
B. Differential Method
C. Hybrid Method

A. Integration Method

a. Global Conductance Model

In the global conductance model, the whole domain is divided into a small number of control volumes. Some of the models with global thermal conductances use experimental data to find overall conductance over the compressor and in some models, it is calculated from correlations in the literature. The objectives are to predict the temperature distribution, calculate suction overheat, and heat generation.

Work in Literature:

Meyer and Thompson [4] developed an analytical model to simulate the temperature distribution of the components of the hermetic reciprocating compressor. The energy conservation equation in its integral form is applied to six control volumes. The heat conductances are calculated by considering only radiation and convection heat transfer between the elements. The heat conductance inside the compressor is evaluated experimentally while heat conductance between shell surface and surrounding is calculated by using correlation of natural convective flow over a flat plate. According to the authors, more accurate results are obtained if considering transient heat transfer instead of steady-state.

Todescat et. al. [9] developed a thermal model for forecasting the distribution of temperature inside a compressor. The author divides the model into 4 control volumes and energy balance is modelled based on the first law of thermodynamics. The governing equations are formed similar to [5] and variation of mass and energy fluxes are taken into account. The equivalent conductances are obtained from the experimental analysis. The overall energy balance is obtained by equating heat transfer from shell to the internal environment is equal to heat transfer from shell to the surrounding. The experimentally obtained coefficients limit their scope as they are sensitive to geometric changes. The formed equations are solved using numerical methods through the simulation program. Todescat [9] shows good agreement between experimental results and results obtained from simulations.

Dutra et. al. [14] adopted the integrated global conductance method for the formulation of a hermetic reciprocating compressor. The whole domain is divided into eight control volumes including an electric motor. The mathematical model involves the integration of three sub-models: 1) Thermodynamic model 2) Thermal model for temperature forecasting 3) Electrical model for the motor. The steady-state energy conservation is applied to all control volumes similar to [10]. The global conductances are explicitly obtained from energy balance based on the methodology similar to [10]. The thermal model is solved by information exchange between three sub-models. The instantaneous mass flow rate is obtained from the thermodynamic model while motor losses are obtained from the electrical model. The whole model is solved by using a coupled solution procedure through a simulation program.

Yang et. al. [15] presented a comprehensive model to predict the compressor performance. The mathematical model comprises the Geometry and Kinematics model, Compression process model, and Overall energy balance model and single phase motor model. The comprehensive model also includes the sub-models such as friction power loss model, leakage model, and valve sub-models. The global conductance model is used for overall energy balance. The energy flow within the compressor is shown using a thermal resistance network. The heat transfer rate is calculated using the ratio of the thermal difference to thermal resistance, and thermal resistance is calculated using empirical correlations. The solution algorithm to solve the model is also presented. The predicted results show good agreement with experimental results.

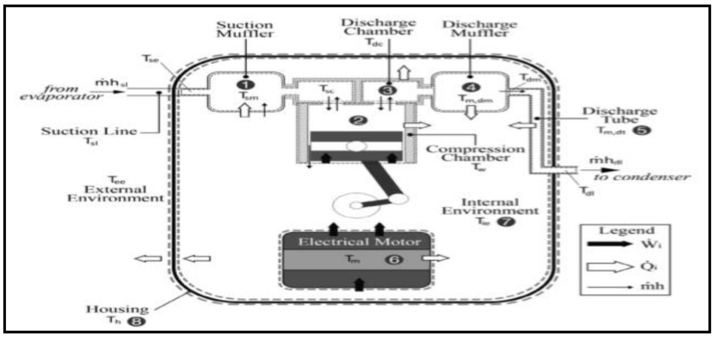

Figure2: The integrated model proposed by Dutra et. al. [14]

b. Thermal Network Model

The thermal network model differs from the global conductance model in a way that the heat transfer coefficients are obtained from heat transfer correlations instead of the experimental method. It considers the contribution of oil flow, radiation heat transfer from the motor, and all convective heat transfers. The thermal network model generally uses a larger number of elements to predict temperature distribution inside the compressor. The main difficulty in the adoption of this model is that the correlations that exactly match all flow conditions including oil flow are limited. The temperature distribution given by the thermal network model is more detailed than the global conductance model.

Work in Literature:

Padhy [16] proposed a numerical model in which the work domain is divided into 22 thermal elements. Model is a thermal network model but the principle of the formulation is quite similar to the global model. The heat transfer inside a rotary compressor is formulated by 22 governing equations results from an analysis of 22 thermal elements. The heat transfer by all modes i.e. by conduction, convection, and radiation is taken into account. The heat transfer coefficients are obtained from correlations available in the literature. The formed simultaneous equations are solved using numerical methods.

Ooi [7] developed a thermal network model using 46 discrete thermal elements. The compressor components are discretized into thermal elements with simpler geometry. Hence it is easy to choose heat transfer correlations available in the literature for each geometry. The heat transfer modes considered for analysis are conduction and convection only. The governing equations are represented in matrix form. The matrix equations are then solved using the Gauss-Jorden numerical method. The author also studied the effect of suction line material component on compressor cylinder temperature. Change from copper to Teflon with the best position of suction muffler gives suction plenum temperature reduction from 76.4 ^{0}C to 67.2^{0}C.

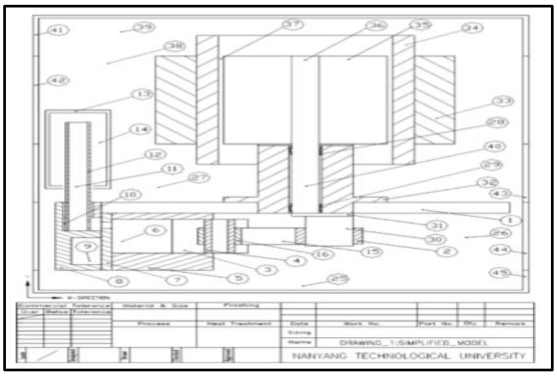

Figure3: Computational domain proposed by Ooi. [7]

Haas [17] presented a thermal network model analogous to [16] and [7]. The author modified model slightly by i) increasing the thermal elements to 63 ii) updating correlations for calculating heat transfer coefficients and iii) detailing oil flow path and temperature distribution along the oil path. The lubricating is treated as a separate computation domain. The data regarding losses, efficiencies are calculated from experiments and used as constant in the analysis. Heat transfer within the shell is considered by conduction and convection only. The compression cycle is considered a polytropic process. Results show good agreement with experimental results.

The integration method of heat transfer modelling is easy to adapt to any compressor. The main drawback of this method is the adoption of exact geometries, calculation speed. Also, this method does not allow 3D heat transfer calculation in solid components, the flow of refrigerant, and the flow of lubricating oil. The 1D conduction is adopted in [17], but that is not enough for complex geometries. Hence some studies in the literature are carried out by using differential methods.

B. Differential Method

This type of model has an objective to forecast heat transfer and fluid flow involved within the system. It provides a detailed analysis of flow behaviour within components of a compressor at a faster rate and lowest cost than experimental methods. As this model involve the use of computers, it provides accurate and quick solution even for complex geometries. Then the domain is discretized into a large number of elements or control volumes and governing equations of mass, momentum, and energy are solved for each element. All modes of heat transfer are taken into account for analysis. This method requires sound simulation skills and several approximations are made to solve governing equations this method is not widely adopted as a design tool but the rate of adoption is growing faster.

Work in Literature:

Chikurde et. al. [18] used a commercial CFD software ANSYS fluent for fluid flow and heat transfer analysis in 1.5TR hermetic reciprocating compressor. The proposed model is 3D and simulation is done at steady-state conditions. The gas is assumed as ideal gas and compression are assumed polytropic. Mechanical and electrical losses are considered as sources of heat generation and radiation heat transfer is neglected. The results obtained from the analysis show a maximum deviation of 7 ^{0}C with experimental results.

Raja et. al. [19] set up a differential model for prediction of the temperature profile in a household refrigerator using a commercial CFD code. The FVM is applied to compressor geometry to solve governing equations. The solution comprises of two steps, firstly the refrigerant domain is solved by considering initial temperature distribution and heat transfer coefficients in solids and in the next step the heat conduction in solid is solved by giving refrigerant temperature fields obtained in earlier step as a boundary condition. Again the updated results are given to the first step and this procedure follows iterations till convergence is reached. The results show a 7.8 % deviation for rotor and 8% for a block with experimental results.

Birari et. al. [20] proposed a steady-state differential simulation model of the compressor using the FVM. The model considers heat generation due to motor losses, friction losses, heat generation inside the compression chamber. The simulation model is solved in two steps, i) Transients heat transfer rate on the compression chamber surface is calculated and it is integrated over the whole domain to get an average value. ii) Heat transfer in solid components and refrigerant heat transfer at suction, discharge, and within the shell is calculated. The velocity and inlet temperature conditions are described as per ASHRAE conditions. The motor losses are obtained from the dynamometer test. The obtained numerical results are compared with experimental data for R22 and R404 refrigerant and it shows a maximum deviation of 16 ^{o}C. The disagreement is justified by the use of motor data other than operating conditions

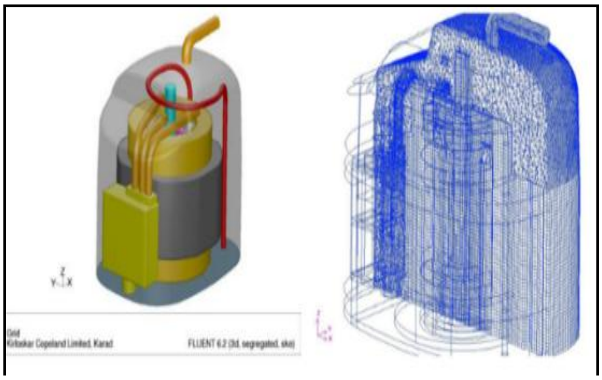

Figure3: Geometry and mesh adopted by Birari et.al. (2006)

Kara and Oguz [21] developed a 3D simulation model using the finite volume method. The compression domain is modelled including the compression chamber, discharge chamber, and valve plate. The heat transfer between solid components is obtained by giving gas temperatures obtained from experiments and heat transfer coefficients calculated from correlations in literature as boundary conditions. The results obtained are compared with experimental data and it shows a maximum deviation of 9^{o}C.

Wu et. al. [22] proposed a 3D simulation model to study temperature distribution in the motor of the R32 hermetic rotary compressor. The computational domain is divided into three sub-domains: i) Refrigerant gas model ii) Stator iron model iii) Stator winding model. Rotor losses are calculated from Anisoft software. The discharge temperature is given as an inlet boundary condition for simulation. The results of the simulation show good agreement with experimental results with a variation of less than 5°C. According to the author, an integral approach to stator winding is sufficient for the thermal study of the motor.

Ozsipahi et. al. [23] presented a 3D model to study the lubrication system of the hermetic reciprocating compressor. The thermal interaction between refrigerant and oil is modelled using a two-phase volume of fraction (VoF) method. To get better results two types of meshing i.e. sliding mesh and moving reference frame mesh is used for analysis. The predicted mass flow rate using CFD shows good agreement with experimental results. This modelling method provides flexibility in compressor heat transfer analysis as it solves both fluid and solid domains. But, this model requires high computational time and optimization is also difficult. Complex phenomena like dynamics of refrigerant in the compression chamber, lubrication dynamics are still difficult with this technique. Hence advancement of this technique is necessary.

B. Hybrid Method

This model combines an integrated model with a differential model to solve complex heat transfer problems. The heat transfer in solid components, refrigerant heat transfer, and heat transfer related to oil can be easily solved by this model. It is a good compromise between accuracy and computation time. It unites the simplicity of the integration model with an accuracy of the differential model. The coupling of the solution of a differential model with an integrated method is necessary for better results. Experimental validation is also required for this model.

Work in Literature:

Almbauer et. al. [24] developed a 3D simulation model based on the hybrid model. The thermal network combines cylinder head, valve pate with a compression chamber. The mass, momentum, and energy conservation equation are solved for the 1-D transient flow of refrigerants. The results provide compressor work, pressure distribution, and heat transfer coefficients for solid surfaces for assumed wall temperatures. In the next step, the 3D solid simulation is solved by giving heat transfer coefficients as boundary conditions. From 3D simulation author heat transfer functions (HTF) are evaluated to characterize thermal exchange. According to the author, it is difficult to calculate heat transfer correlations with the thermal network method.

Ribas [10] developed a hybrid formulation model by combining the global conductance model with a finite volume-based differential model to forecast temperature distribution inside the compressor. The solution domain consists of three tasks; i) Thermodynamic modelling of compression cycle ii) The conduction heat transfer calculation from differential model iii) The heat transfer of refrigerant at different components such as suction system, discharge system, motor, shell, etc. The integration model adopted is very similar to [9] and the overall thermal conductances are also calculated from experimental results. These models are solved in a coupled manner by an iterative procedure. The results well fit with experimental results with a maximum of 5°C deviation.

Sanvezzo [2] adopted a hybrid simulation model for compressor heat transfer analysis. The solid heat transfer is calculated by solving the differential model. The integrated model adopted is very similar to [6]. In the integration model, the heat transfer coefficients for heat transfer between solid components and refrigerant are calculated from correlations available in the literature. The effect of lubricating oil is also taken into consideration. The two models are solved iteratively in a coupled manner. It shows a maximum deviation of 15 ^{0}C with experimental results.

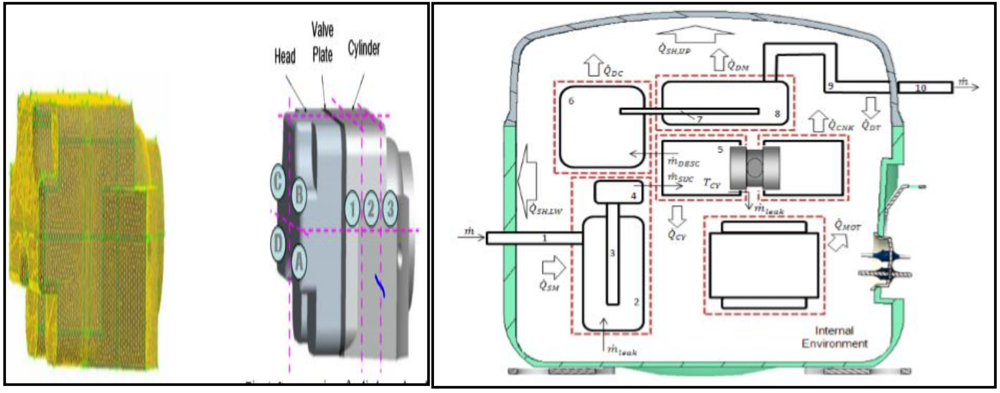

Figure4: Geometry and mesh adopted by Birari et.al. (2006)

Posch et. al. [25] presented a simulation model that consists of three main parts. The gas flow simulation and heat transfer in solids are simulated using commercial CFD code, while oil and gas interaction is simulated by using a lumped integrated model. The refrigerant in the shell is considered as one control volume and the oil domain is divided into three control volumes. The solution algorithm starts with an initial guess of temperature in all parts, gas, and refrigerant oil. The commercial CFD code used is Ansys Fluent. All three domains are solved iteratively till the convergence criteria is reached. The calculated temperatures show a maximum deviation of 4.2^{o}C with experimental results.

III. CONCLUSION

The reliability and efficiency of the compressor are greatly affected by thermal losses inside the compressor. The overheating of the suction gas of the compressor is the main reason behind the losses. The experimental methods adopt various advanced devices like quick response thermocouples, heat-flux sensors, infrared thermography, optical encoder, pressure sensors, and cold wires in addition to thermocouples. In concern to numerical methods, the adoption of various numerical techniques is growing continuously. The integration model is good for optimization, quick simulation, and approximate results at the lowest cost but not accurate for complex geometries and drastic changes. Conversely, a differential model can be easily adopted for complex parts and drastic changes, it also gives detailed temperature distribution but needs special skills and high cost of computation. The hybrid model is a compromise between the above two, it gives solid heat transfer along with better refrigerant heat flow at the lowest cost. The choice of the numerical method is based on the need for accuracy and complexity of the model. The best way of compressor design is to unite both numerical methods with experimental analysis. It provides a better understanding of thermal behaviour and ways to tackle the overheating problem.

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