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HEAT TRANSFER MODELING AND SIMULATION OF RECIPROCATING COMPRESSORS - A REVIEW

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Abstract

Modeling cylinder heat transfer process coupled with the kinematic, fluid flow and valve dynamic processes is essential for determining the actual performance of any compressor. Heat transfer occurs primarily due to conduction and convection in compressors. Control volume for heat transfer study is the space between the cylinder head and piston. Heat transfer between the gas and cylinder, cylinder wall and surrounding and the gas and valves are calculated using various heat transfer correlations for conduction and convection. Proper heat transfer modeling is useful for determining the cylinder pressure and temperature which in turn useful in calculating the indicated work done and other parameters like actual torque. Analytical formulations of heat transfer processes are challenging while trying to create an entire compressor performance modeling. To obtain the performance

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parameters of the compressors, all the processes are coded with algebraic equations for their simplicity and over all mathematical models is obtained. Performance of a compressor can be understood from the Pressure Volume diagram which can be mathematically produced by considering all the individual effects. An effective heat transfer model needs to be incorporated with the overall mathematical model of a reciprocating compressor. This paper reviews the open literature available for the development of heat transfer model for reciprocating compressor.

1. Introduction

1.1. Mathematical models

Mathematical models are built using numbers and symbols that can be transformed into functions, equations and formulae [1]. Building a mathematical model for any real complex system based on the underlying the scientific concepts reduces the lead time involved in the design process. Irrespective of the system involved, the general approach is common and listed below [2]:

1. Identify the problem, define the terms in the problem and draw diagrams where appropriate.
2. Start with a simple model, stating the assumptions.
3. Identify the important variables and determine how they are relating to each other.
4. Develop formidable mathematical equations with proven scientific background expressing the relationship between variables.
5. Solve the above set of equations for reasonable outcome.
6. Refine the above process by removing assumption one by one until to get a model closer to real world observations.

The following Figure 1 shows the flow chart for mathematical modeling. The flow chart is abstract one and can be modified depending upon the nature of the physical problem.

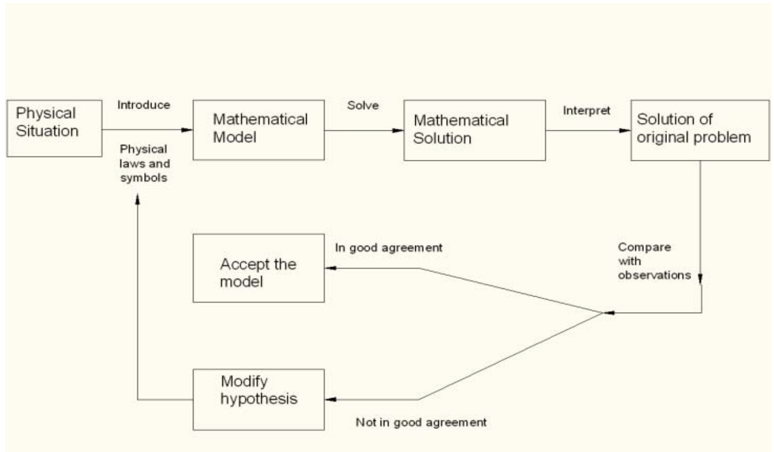

Figure 1. Flow chart for mathematical modeling.

Simple mathematical models for studying the performance of reciprocating refrigerant compressors developed in the year 1974 by Prakash and Singh [3, 4]. These models are the keys for present day research in compressor modeling.

1.2. Reciprocating compressors

Compressor is a machine providing fluids at high pressure. The required work for pressure conversion is delivered externally. Reciprocating compressors are used in chemical industries, foundries, breweries, process plants, refrigeration and air conditioning equipment and automotive systems. These are positive displacement machines where they increase pressure by reducing the volume. This means that they are taking in successive volumes of fluids, which are confined within a closed space, and elevating it to a higher pressure by means of a piston which is displacing agent. Single stage and multi stage are commercially available and single stage develops pressure in the range of 1-9 bar and multistage up to 100 bars. Compressing ethylene to pressure upwards to 300 MPa (3000 bar) for the purpose of producing low density polyethylene - LDPE require reciprocating compressor machinery. Load reduction is achieved by unloading individual cylinders. Typically, throttling the suction pressure to the cylinder or bypassing air either within or outside the compressor is the technique. Capacity control is achieved by varying speed in engine driven units through fuel flow control. These compressors are available either as air cooled or water cooled in lubricated and non-lubricated configurations.

Reciprocating compressors consist of a crankshaft driven by either gas or engine attached to a connecting rod, which transfer the rotary motion of the crank shaft to the reciprocating motion of a piston. The piston compresses the air to increase its pressure. Air enters the cylinder through a suction valve at suction pressure and is compressed to reach desired delivery pressure. At delivery pressure, the air is discharged out of the compressor through delivery valve. Figure 2 shows the sectional view of the compressor.

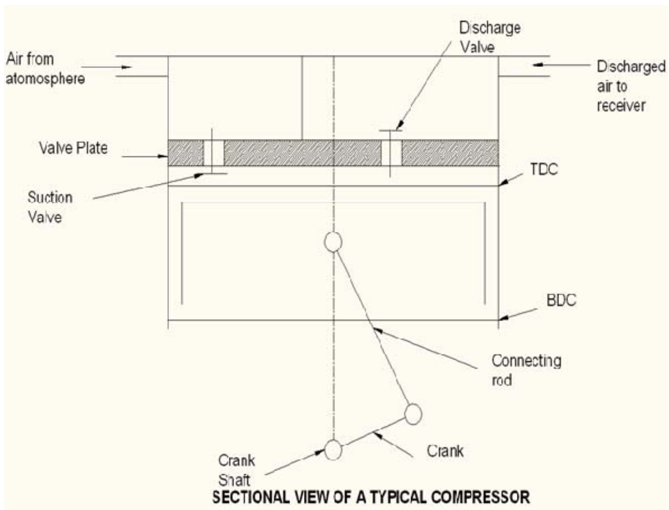

Figure 2. Sectional view of a typical compressor.

1.3. Heat transfer

The principal modes of heat transfer inside the casing of a compressor are conduction and convection [5, 38]. Radiation is not predominant due to small temperature differences between the components of the compressor. Inside the compressor, forced convection turbulent flow inside concentric annular duct model is considered and for the fluids passing through the valves, forced convection flow over a flat plate model is considered [6]. In fully developed turbulent flow conditions, traditional expression for the calculation of heat transfer in presented by Dittus and Boelter [8]. For high speed applications, a modified set of equations are presented by Gnielinski [9]. Spang [7] has consolidated the correlations for convective heat transfer and are listed below:

The heat transfer coefficient can be calculated by

$$Nu_d = 0.023\,\mathrm{Re}_d^{0.8}\,\mathrm{Pr}^{0.4} \text{ for compression and delivery strokes} \quad (1)$$

$$Nu_d = 0.023\,\mathrm{Re}_d^{0.8}\,\mathrm{Pr}^{0.3} \text{ for expansion and suction strokes.}$$

In the case of high speed flow, the above equation is modified as

$$Nu = 0.0214(\mathrm{Re}^{0.8} - 100)\,\mathrm{Pr}^{0.4}\,. \quad (2)$$

Modeling heat transfer using numerical techniques have developed over the years starting from finite element method, finite difference technique, finite volume method and other mesh free methods. Analytical modeling of the dynamic processes using energy exchange (II law of heat transfer analogy) to predict the impact of heat transfer has been carried out [20]. Suction gas heating and discharge gas cooling are the two important mechanisms influence the heat transfer on compressor performance. Heat transfer to the suction gas occurs in all the three modes of heat transfer. Conductive and convective heat transfer occurs as the gas flows through the cylinder and valve openings and radiation heat transfer occurs in suction pipes. In the refrigerant compressors, heat transfer modeling has been incorporated in the overall simulation models for compressor performance. (Scheideman et al. [11], Meyer and Thompson [13], Hiller and Glicksman [12] and Prakash and Singh [3].

Present day researchers are focusing on fractional calculus, the branch of mathematics deals with the applying real number powers or complex number powers of the differential operator. Heat conduction and associated problems are solved effectively using fractional derivative heat transfer models [50-52]. In the literature reviewed the technique of fractional derivate /fractional variation iteration methods are not used in developing heat transfer models for reciprocating compressors.

2. Mathematical Modeling of Compressor

2.1. Cylinder kinematics

Modeling cylinder kinematics is vital for any reciprocating compressor. Due to cylinder kinematics, flow losses are encountered. The valve losses are attributed to the kinetic energy loss due to flow restrictions in the gas path while flowing through valve openings and ports. Pandeya and Soedel [14-16] demonstrated that kinematic arrangement also plays a role in effecting losses and explained the arrangements where the suction and discharge plenums are located away from the axis of the rotation of the shaft and the reverse reciprocating arrangement. A velocity of the gas through valve opening and the ports depends not only on effective flow area and also the rate of change of volume of the cylinder space which is directly dependent on kinematics. In general, for crank rotation or a piston displacement, cylinder volume is calculated. Cylinder volume is calculated based on the piston movement using the following equation [39]

$$V = V_c + \frac{\pi}{4} D^2 r \left\{ (1 - \cos\theta) + \frac{r}{2l_c} \sin^2\theta \right\}. \tag{3}$$

The above transcendental functional equation can be changed to a power equation using Taylor’s theorem for more accuracy is proposed to counter the error produced by trigonometric functions.

2.2. Fluid flow

Fluid flow models are grouped into either steady state or dynamic models depending upon the degree of complexity. First law of thermodynamics is used for developing these models [42, 43]. These models considered that the mass flow rates of suction and discharge are equal. A dynamic model of compressor for on-off cycling operation was developed and model depicted the influence of suction and discharge mass flow rates and the electrical power [44]. There is always a significant transfer of energy between the moving fluid and solid structure [45]. Coupled numerical technique, fluid structure interaction is proposed to link the flow characteristics and valve movement.

2.3. Thermodynamic processes

Mathematical modeling of the dynamic processes in a compressor involves knowledge of various forms energy exchange occurring in the system. Thermodynamic models used can be divided into two. One is empirical approach based on laboratory experiments [46-47]. The other is the theoretical approach modeling compression and expansion as adiabatic [48-49]. The thermodynamic processes describes the successive states of the working fluid as it flows through the suction valve, undergoes compression in the cylinder, exhausts through the discharge valve and at the same time heat is transferred to and from the working fluid [4].

2.4. Valve dynamics

Modeling dynamics of self-acting compressor valves is essential for the accurate calculation of compressor performance. The difficulty arises mainly due to the interaction of flow of compressible gas and a dynamics of mechanical system [20]. Valve movements were modeled as single degree of freedom vibratory systems during early mathematical models [32] produced. Later stages, finite element methods, boundary element methods and computational fluid dynamic methods were used. At present, researchers are focusing on using fluid structure interaction (FSI) analogy for understanding valve dynamics. The predominant forms of compressor valve failures are fatigue and bending failures [33].

3. Heat Transfer Modeling of Compressor

3.1. Cylinder heat transfer

The instantaneous heat transfer between the cylinder walls and gas has an utmost effect on the compressor performance especially during the compression cycle. Noticeable amount of heat flux occurs in the interface, from the cylinder to the gas during suction and from the gas to the cylinder during compression. The importance of heat transfer has been discussed [20-22], but the discussion does not conclude about the importance of heat transfer in determining the compressor efficiency and the methods to control the effects of heat transfer.

One can study the heat transfer approach by the following three ways. Firstly combining experimental measurements with heat balance to identify the overall heat transferred to the gas [23-26]. The approach is straight but does not give insight into the mechanism of heat transfer. Secondly using numerical procedure based on models based on first law of thermodynamics [21, 27, 28]. Here designer can play around the parameters involved in the model to have further predictions. These models are suitable regardless of the geometry of the compressors and to an extent even the type of compressors. The disadvantages of these models are their dependence of experimentation for heat transfer coefficient relations. The third approach is using basic differential equations describing the flow and heat transfer of the gas inside the cylinder space is solved using finite difference techniques [29]. This was applied firstly to piston cylinder configurations [30] and extended further and applied to the geometry of a compressor [31].

Experimental evaluation of the parameters influencing heat transfer is difficult due to the size and speed of the compressors. Some in-cylinder heat transfer correlations have been developed to account heat transfer effects in compressor performance. Improvements in sensor and instrumentation technology have helped in producing simultaneous measurements of in-cylinder temperature, pressure and heat transfer rates [10]. From the thermodynamic point of view, heat transfer from the gas to the surrounding during the working processes will reduce the compressor work. Adair identified by experimentation that during the thermal inertia of the cylinder material, its temperature variation is smaller than the gaseous temperature variation and concluded that temperature gradients on the cylinder wall, can be taken as the average values during one cycle [18]. The data correlations for the cylinder wall temperature, cylinder head temperature, temperature of the gas in the suction plenum, temperature of lubricating oil are produced by Liu and Zhou [19] are reasonably good to calculate them and identified pressure ratio, suction temperature and speed influences the heat transfer.

As per the first law of thermodynamics, the change rate of heat transfer can be found by

$$dQ = dU + dW. \tag{4}$$

Differentiating the above equation, with respect to crank angle,

$$\frac{dQ}{d\theta} = \frac{\gamma}{(\gamma - 1)} p \frac{dV}{d\theta} + V \frac{1}{\gamma - 1} \frac{dp}{d\theta}. \tag{5}$$

By accounting the convective heat transfer between the wall and the gas or the gas and the wall, the above equation may be modified in to,

$$\frac{dQ}{d\theta} = \frac{\gamma}{(\gamma - 1)} p \frac{dV}{d\theta} + V \frac{1}{\gamma - 1} \frac{dp}{d\theta} + hA_s(T_g - T_w). \tag{6}$$

For conventional mathematical models, the above equations hold well provided that the convective heat transfer coefficient is found correctly.

Muellner modeled the heat flow through the walls using special wall functions that couple the heat flux density at a certain point of the wall with the gas temperature in this point using Reynolds' analogy between momentum and energy transport [40].

3.2. Valve heat transfer

The typical reed valve assembly has two or four reeds which share the same basement and upper stops. The compression ratio inside the cylinder is at the level of 8-12 bar, therefore, there is tremendous change of pressure and temperature of a working fluid inside the cylinder. The valves have to withstand the high temperature also. In diesel and petrol engines, studies have proved that the valve insulation helps to improve the life [34]. The experimental set up to gather heat transfer characteristics is difficult because a probe has to be attached with a valve and accurate data acquisition mechanisms to be in place and also due to the high speed. Numerical investigations are made over the years to understand the effect of heat on valve performances. Researches were carried out to identify the appropriate heat transfer correlations in terms of non-dimensional numbers. One of the correlations suggested being good while considering that there is a transient flow inside the suction and discharge chamber is provided [35]. The expression is shown below:

$$Nu = 0.0235(\mathrm{Re}^{0.8} - 230)\left(1 + \left(\frac{d}{L}\right)^{\frac{2}{3}}\right)(1.8\,\mathrm{Pr}^{0.3} - 0.8). \tag{7}$$

The above expression is valid for Prandtl numbers above 0.8 and Reynolds number above 2300. Heat is transferred from valve to working fluid during suction and first part of compression and from working fluid to valve during the remaining part of compression and exhaust processes.

4. Conclusion

Compressors volumetric efficiency is reduced due to the heat transferred to the fluid during suction. Heat transfer inside the cylinder is mainly due to conduction and convection. The effect of convection is considerably less compare to conduction. Computational technique called FSI (fluid structure interaction) is useful in integrating fluid flow, heat transfer and valve dynamic. Using dimensionless parameters involving Reynolds number, Prandtl Number and Nusselt Number correlations, heat transfer coefficient can also be determined. The amount of heat added to the working fluid and the heat rejected from the working fluid is calculated [36] by combining the equations of conduction and convection. Integrating effective heat transfer models which includes the account of flow and valve dynamics with the cylinder kinematics may help to create efficient mathematical model for compressor performance predictions.

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