Applied Thermal Engineering 61 (2013) 149–156

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Experimental investigation on valve impact velocity and inclining motion of a reciprocating compressor

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HIGHLIGHTS

- The inclining angle of discharge valve becomes uncertain if pressure ratio is larger than 2.55.
- The inclining angle decreases with the increase in valve installation distance.
- The piston velocity and volume of compression chamber have a direct impact on impact velocity.

ARTICLE INFO

Article history:
Received 10 January 2013
Accepted 28 July 2013
Available online 6 August 2013

Keywords:
Working cycle
Reciprocating compressor
Valve dynamics
Impact velocity
Inclining angle

ABSTRACT

The working cycle of a reciprocating compressor results in the periodic impact of compressor valves. In order to find out the main cause for the excessive impact stress, this paper presents an experimental investigation on the valve dynamics especially the inclining angle and the impact velocity. The suction and discharge ring valves were redesigned and three displacement sensors were installed on top of the valve rings to measure the rings' instantaneous 3D motions, based on which the main factors that influenced the valve movements were identified by varying the valve installation position, clearance, working condition and the rotational speed. The inclining motion hardly happens as the valve is opening, while severe inclining motion takes place when the discharge valve is closing. When the pressure ratio is larger than 2.55, the inclining angle becomes uncertain because of the short time span of discharge process. The piston velocity and the volume of compression chamber at the valve opening moment have a direct impact on the maximum impact velocity. It displays a quick increase with the increase of pressure ratio and rotational speed while the valve installation position and the clearance have little influence on the maximum impact velocity. This experimental measuring method and results could provide useful information for both valve testing and optimization of valve reliability.

1. Introduction

Reciprocating compressors have been widely applied in chemical, petrochemical, gas, and general industry processes, and the operation of reciprocating compressors is closely linked to the reliability and efficiency of the suction and discharge valves. According to an industry investigation, valves afforded 36% of compressors' unscheduled shutdowns [1]. There are many causes contributing to the valve failure, including corrosive contaminants, liquid slugs, high cycle fatigue and abnormal mechanical motions of valves [2,3]. Manufacturers have made many improvements in valve material and structure focusing on the reduction of fatigue and impact stresses on both the valve plate and the springs. Klaus [4] even developed a semi-active compressor valve to control the impact speed against the seat or limiter, but abnormal valve motion has not been fully understood. It has been proved that poor valve movement is the main cause for valve failure and high flow resistance [5,6].

Several past studies have been conducted to investigate the regulations of valve dynamics in reciprocating compressors. Some of them paid more attention to the simulation of valve dynamics. In 1950, the first simulated model was a single-degree-of-freedom system, established by Costagliola [7] to describe the valve motion in the form of two non-linear differential equations, which was known as Basic Valve Theory (BVT). Based on this approach, Elhaj [8], Schoonmaker [9], Nieter [10] and Bassi [11] improved the model by taking more aspects into account, such as heat transfer, fluid leakage, stiction effect and pulsations in suction and discharge

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http://dx.doi.org/10.1016/j.applthermaleng.2013.07.046

valve chamber and so on. But regarding to valve dynamics, semi-empirical coefficients were still applied to calculate the gas force and mass flow rate acting on and flowing across the valve. In addition, this approach could not help to understand the flow conditions and valve motion in detail. Modern methods were inclined to induce commercial CFD software to simulate the thermodynamic process and 3D dynamic behavior of valves in reciprocating compressors, taking the fluid–structure interaction (FSI) into account. Choi [12] established a theoretical model to analyze the dynamic behavior of reed valves in a linear compressor, and he found that the preload was considered to be the core factor that affected the behavior of reed valves in linear compressors. Matos's [13,14] computational model considered the cylinder region and the movement of piston, then by using different inlet conditions, he obtained some preliminary results of the reed valve motions and the flow conditions across the valve. In 2006, he [15] proposed a two-dimensional methodology to simulate the complete compression cycle of reciprocating compressors. Pereira [16] presented a three-dimensional numerical model for the analysis of small reciprocating compressors employed for household refrigeration purpose, taking into account the flow in the cylinder and through valves, as well as suction and discharge mufflers. Steinrück [17] established three different models (one-, two-, three-dimensional) to analyze the interaction between internal waves and the dynamics of passive plate valves, and meanwhile, the application range for each model was clearly pointed out.

Although some of the above mentioned simulation models were claimed to be validated by the experiment, the experimental setups were not introduced in detail. And in fact, there are some difficulties to measure the displacements of valves. Prasad [18] measured the displacements of suction and discharge valves by using optic displacement sensors, but the results were less accurate. Buligan [19] developed a measurement method for compressor valve lift based on a single-point Laser Doppler Vibrometer (LDV), and this measurement required a special compressor case equipped with transparent windows for optical access to the valves. Based on Buligan's measurement method, Nagy [20] and Lang [21] validated their theoretical compressor and valve model and the adjustments were also carried out to study the effects of various valve parameters. Ludu [22] installed two endoscopes consisted of a thin fiber-optic bundle into the valve chamber so that valve movement could be obtained through clear pictures, and the valve lift was quantified by digital picture processing. Ma [23] had a close introduction about the experimental setup in which he used an eddy current displacement sensor to measure the discharge reed valve displacement and meanwhile, conducted a sensitivity analysis by varying the design parameters such as pressure ratio, valve lift, spring stiffness and rotational speed. He concluded that low pressure ratio, smaller valve lift and low rotational speed were optimal for the valve life and low rotational speed could also decrease the pressure loss across the valve.

Among all these methodologies mentioned above, they mainly focused on the measurement of reed valve for hermetic household compressor for its large measured areas, but concerning to ring or plate valves, the width of them are usually less than 15 mm, which produces big trouble for displacement sensors. Klaus [2] performed a single impact test of plate valve using a burst-membrane shock-tube, and three optical position probes were instrumented on the valve plate to monitor the position of valve plate. Then he applied this measurement method to the discharge valve of a 186 kW reciprocating compressor and one consistent empirical relationship between impact angle and plate velocity was found when changing operating conditions, geometry, rotational speed. Also, he claimed that other probabilistic relationships between these parameters were established but not described and analyzed in detail.

Considering the lack in experimental research on ring valve motions, a special experiment was creatively designed to measure the 3D motion of ring valves in a modified reciprocating compressor. Based on the measurement, both the valve impact velocity and the magnitude of inclining motion were obtained. In order to identify the main factors that greatly influence the valve dynamics, tests were carried out under different conditions by varying rotational speed, pressure ratio, valve installation position and clearance.

2. Experimental setup

2.1. Modification of V-type air compressor and its valves

There are many factors that influence the valve performance, such as the working conditions, rotational speed, valve installation position, valve structure and even the volume of clearance. In order to figure out the main factors that influence the performance of compressor valves, a test rig was built up by modifying the stage one of an existing V-type two-stage reciprocating air compressor and its valves as Fig. 1 showed. Ring valves were selected for this compressor and installed on top of the cylinder head in the suction and discharge chamber. The width of the original valve rings in stage one was only 8 mm, while the diameter of eddy current displacement probe reached 12 mm. To guarantee the accuracy of the measurement, the measured area should be at least 1.2 times the area of the displacement sensor. Thus the width of the rings was enlarged to 15 mm and the valves of stage one were redesigned based on Soedel's valve theory [24]. Fig. 2 showed the cut views of cylinder head assembly with new suction and discharge valves. Each valve consisted of 2 rings instead of three ones of the original valves. And the specific compressor and valve parameters were introduced in Table 1. Additionally, another two cylinder heads were also designed with different valves installation distance L so as to identify its influence on the valve motion as shown in Fig. 1. An iron plate was added to increase the height H between the cylinder head and the cylinder as Fig. 2 showed so as to figure out the influence of the clearance volume on the valve movement.

2.2. Measuring system

The material of the valves is 3Cr13. In order to monitor the 3D motions of the valves, three eddy current displacement sensors

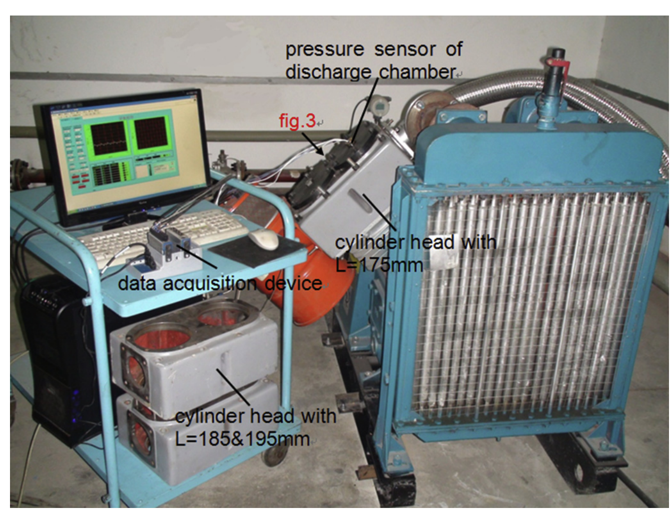

Fig. 1. Experimental setup for the test of valve dynamics.