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ENDOSCOPE VIDEO OF COMPRESSOR VALVE MOTION AND PRESSURE MEASUREMENT ASSIST SIMULATIONS FOR DESIGN IMPROVEMENTS

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1. ABSTRACT

Market pressures demand that modern refrigeration compressors should be more efficient, more durable and quieter than ever before, so thermodynamic modelling techniques are being used to simulate compressor performance and to study design changes for improved products. Simulation without validation cannot be relied upon so measurements must be made of pressure, temperature and valve motion inside the compressor to confirm that the numerical models are correct and to give confidence in future simulations. However, in the past, it has been extremely difficult to make measurements inside a refrigeration compressor with a bore of less than 25 mm without disturbing the parameters being measured. It is made more difficult by the fact that signals have to be brought out through the shell which is hermetically sealed. This paper describes a new technique which has been used to overcome these problems.

Two endoscopes using a thin fiber-optic bundle were installed in a compressor so that video recordings could be made of the suction and the discharge valve movement. High accuracy, piezo-electric pressure transducers were installed to measure the dynamic suction and discharge pressure as well as the pressure in the cylinder. A crank angle position marker was installed so that the signals could all be related to piston position and to each other on a time basis.

The paper describers how all this equipment was fitted into the confined space. Also shown are typical results of the tests performed. Clear pictures of the movement of both valves were obtained and the valve lift was quantified by digital picture processing. The valve motions could clearly be related to pressures recorded before and after each valve so the effect of the design changes could be seen and understood. These new measurement techniques are ideally suited to reed, plate or poppet valves as used in compressors for other duties such as air and gas compression.

Some thermodynamic cycle modelling was also carried out using a simple reed valve simulation approximation and some correlation was obtained.

2. INTRODUCTION

Simulation of the compressor thermodynamic cycle can be a powerful tool to investigate the effects of design changes and to solve refrigeration compressor typical problems such as efficiency optimisation or noise reduction. Once the compressor thermodynamic cycle calculation code is validated and a good calculation to measurement correspondence is achieved, an extended range of design variants can be investigated analytically at acceptable costs and within relatively short time frames. The basis of the calculation code validation has to be produced by detailed experimental investigations. For compressors employing reed valves, such as refrigeration compressors, additional to static pressure, temperature, refrigerant flow and electrical power measurements, information on the valve motion and on the dynamic refrigerant pressure at several compressor locations enable a better understanding of the in compressor processes and offer a better calculation code validation basis.

The task of the work described in this paper was to perform measurements on a hermetic refrigeration compressor to record characteristics relevant to the thermodynamic cycle calculation code validation. The results of the experimental work should furthermore enable a better understanding of the processes taking place in the compressor. Special emphasis was to be given to experimental means of learning more about suction and valve motion. On completion of the experimental investigation thermodynamic cycle calculations were to be performed for verifying the potential of an existing one dimensional thermodynamic cycle code with respect to compressor cycle simulation. The work was performed in the form of a project initiated by Electrolux Compressors of Italy; AVL List GmbH of Austria carried out the valve motion video investigation, the dynamic pressure measurement and the thermodynamic compressor cycle calculation.

This paper presents the experimental investigations: suction and discharge valve motion visualisation and measurement using an endoscope video system, dynamic refrigerant pressure measurements and the analytical investigation using a one dimensional thermodynamic cycle calculation code.

The Electrolux GLY75AVL prototype compressor which was subject to the work described in this paper is a derivative of the Electrolux GLY75AA model. The GLY75AA is part of the high efficiency compressor family for the R134a refrigerant range. It is a hermetic one cylinder piston compressor for low back pressure household refrigerators. The compressor is driven by a resistance starting induction running / resistance starting capacitor running motor at a nominal compressor speed of 2915 rpm. The bore x stroke of the GLY75AVL are 24.29 x 15.91 mm.

In the course of the work several suction and discharge valve configurations such as for example suction valve with and without lift stop, were tested and compared. Most of the measurements were carried out for three refrigerant evaporation temperatures 238, 249.7, and 263 K; the corresponding refrigerant compressor suction pressures for the R134a refrigerant are 0.661, 1.148 and 2.006 bar, respectively.

3. VALVE MOTION VISUALISATION AND MEASUREMENT USING THE AVL VIDEO SYSTEM 513

3.1 The AVL Digital Video System 513

The suction and discharge valve motion was visualised using the fully digitised triggerable video system, 'AVL Digital Video System 513', **Fig. 1**. The system consists of a digital CCD colour video camera, a Pentium 200 Pro PC, AVL viewer software, VSK interface card, a frame grapper card and an illumination unit. A highly integrated PC plug-in card for process synchronisation and implementation of powerful trigger capabilities allows exposure tolerances of 0.1 degree crank angle for true-angle recording independent of compressor speed, and tolerances of 2 μs for time delayed records. An endoscope, fitted directly to the objective of the video camera, provides the optical access into the compressor.

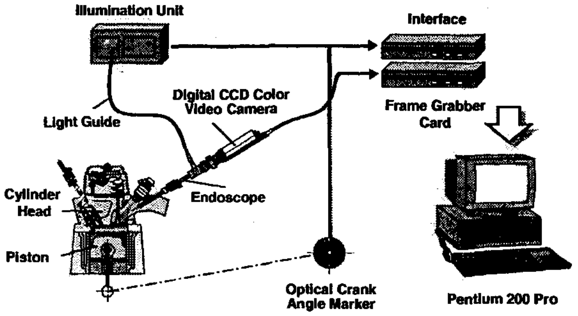

Fig. 1 The AVL Digital Video System 513

3.2 Experimental Set-up

In order to visualise the compressor valve lift motion under realistic conditions, a typical flowmeter compressor test bed installed by Electrolux on an AVL test bed for endoscopic video investigations. The test bed is at ambient temperature but thermoelectric resistors were installed to control the temperature of the gas entering the shell at 32 °C, as required by typical testing conditions. The refrigerant mass flow rate is measured by the rotameter calibrated with tables based on pure gases.

The compressor as such was encased in a special hermetic shell (larger than the production shell). At the bottom of the shell an electrical resistance, monitored by a temperature sensor, helps the warming up of the compressor oil in order to achieve thermal condition as similar as possible to the condition of a compressor running in a typical shell and in a temperature controlled room. The suction pipe inside the shell has been extended to have the same distance between suction muffler inlet and suction pipe as in normal production models. A dedicated fixture was produced to install the AVL 364 optical crank angle marker providing the video system with trigger and CDM signals.

The compressor is fixed rigidly to a plate inside the lower test shell housing. This plate is screwed to the walls of the lower shell. The endoscopes are passing through the test shell walls through adjustable windows. These are screwed to the test shell wall after the endoscope position was adjusted accordingly. Due to this arrangement a rigid endoscope to compressor connection was guaranteed. The video camera capturing the valve motion was mounted outside of the test shell.

3.3 Endoscope Arrangement

For endoscope video investigation on compressors of a relatively small size as the GLY75AVL compressor the endoscope diameter should be as low as possible in order to allow such an investigation in the first place and to minimise the additional dead volumes introduced to system. The diameter of the endoscopes used was 3.62 mm. Special care was taken to minimise the additional cylinder dead volume introduced by the suction valve endoscope which is installed into the cylinder. The discharge valve endoscope was installed into the discharge plenum of the cylinder head. Thus, it didn't introduce an additional cylinder dead volume. Endoscope design specific dead volumes have been eliminated by filling them with epoxy for both suction and discharge valve endoscopes. Pictures showing the endoscope arrangement are shown in **Fig. 2**

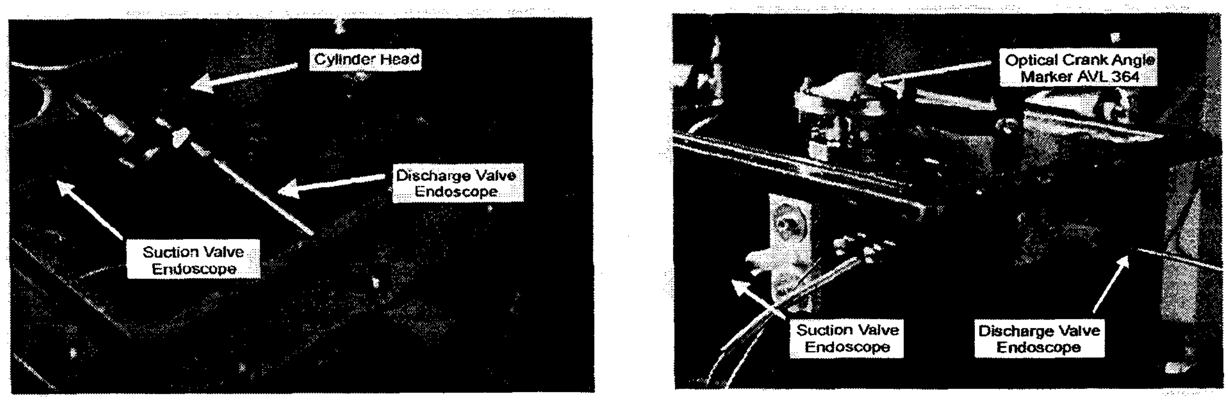

Fig. 2 Endoscope Arrangement

The suction valve endoscope was installed through the crank case and into the cylinder in a right angle to the cylinder axis. The suction valve endoscope was pointed towards the center of the suction hole in the valve plate. The additional cylinder dead volume introduced by the suction valve endoscope was 47 mm^3. A detail of the initial suction valve endoscope arrangement variant is shown in **Fig. 3** The discharge valve endoscope was installed frontal through the cylinder head and into the cylinder head discharge plenum. The endoscope housing axis is parallel to the cylinder axis. Thus, in order to visualise the discharge valve motion an optical agle of 70 deg (angle between endoscope housing and optical axis) was chosen. The optical axis of the endoscope was pointed towards the center of the discharge hole in the valve plate. A detail of the suction valve endoscope arrangement is shown in **Fig. 4**

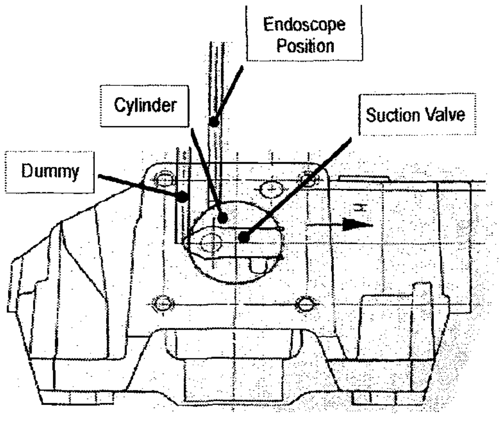

Fig. 3 Suction Valve Endoscope

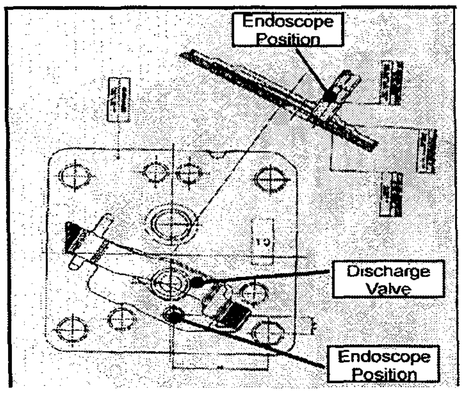

Fig. 4 Discharge Valve Endoscope

3.4 Valve Lift Evaluation

The compressor was started and operated, until stabilised conditions in terms of pressure, flow rate and temperature were reached, before starting the video investigations. Two video operation modes were used: scan mode with one image per deg. crank angle and a resolution of 0.5/1.0 degree crank angle and repetition mode with ten repetitions per degree crank angle and a resolution of 1.0/5.0 degree crank angle. The quality of the valve motion videos was good. The events of valve opening and closing were clearly visible. The results from the endoscope video investigation were digital video sequences, showing the valve motion. These videos can be run using the AVL viewer software. To generate additional quantitative valve lift information, the digital images were processed by using Adobe® Photoshop® 5.0 software.

Images of the actual valve position during the open valve phase were copied into an image of the closed valve, thus making both positions visible in a single image. The distance between both valve positions (valve lift) was measured in the suction and discharge hole axis. A separate pin with a millimeter scale was inserted along the suction and discharge hole axes to create a correlation between the physical (actual) size and the measured (scaled) value, thus defining a calibration factor. According to this procedure the measured valve lift was defined as the distance the valve lifts along the suction and discharge hole axis.

The suction valve opens generally for a relatively long time and usually bounces three times between closed and maximum lift within one cycle. The discharge valve opens for a shorter time and doesn't have a pronounced bouncing behaviour. These are expected results due to more pronounced pressure differences along the discharge valve compared to those along the suction valve. The opening and closing timings as well as the open duration and maximum valve lifts are different for the three suction pressure levels tested, **Fig. 5**. The suction valve design with valve stop eliminates the bouncing behaviour of the suction valve, **Fig. 6**. This is expected to be beneficial with respect to the fatigue stress and noise. Nevertheless the COP is reduced by 2 – 3% by this design measure.

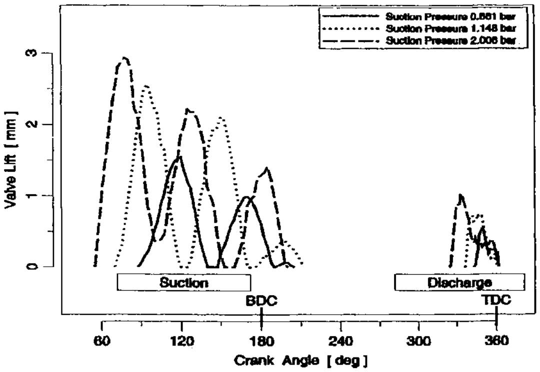

Fig. 5 Video Measured Valve Lift for Different Suction Pressure Levels

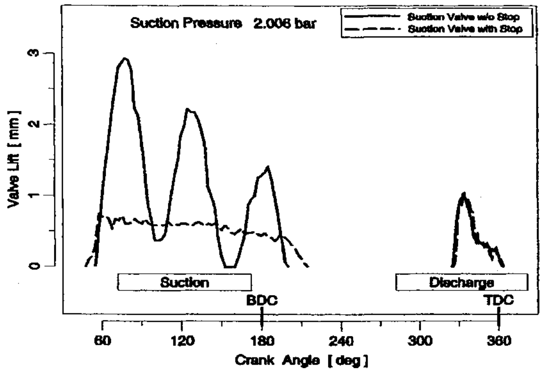

Fig. 6 Video Measured Valve Lift Suction Valve Design Comparison

4. DYNAMIC PRESSURE MEASUREMENT

Developing a good basis for calculation model validation and a better understanding for the processes taking place in the compressor called for detailed compressor performance measurements. As part of those measurements a special interest was invested in recording dynamic refrigerant pressures at several compressor locations. For this purpose the compressor was instrumented accordingly, was encased in the same test shell as for the valve motion visualisation work and was installed on one of the Electrolux test beds.

A relative extensive range of measuring points were installed:

- the dynamic pressure was measured in the cylinder, suction muffler, cylinder head discharge plenum, 1st and 2nd discharge muffler and in the external discharge pipe

- the static pressure was measured inside the shell, the suction muffler, cylinder head discharge plenum, 1st discharge muffler and in the external discharge pipe
- the temperature was measured inside the shell, the suction muffler, cylinder head discharge plenum, 2nd discharge muffler and in the external discharge pipe

The dynamic pressure in the suction and discharge system was measured using the AVL GM12D piezoelectric pressure transducer. It's compact dimensions (19 mm height, M 5 x 0.5 thread) were significant for this application, where the compressor is small and the space inside the test shell is limited. A top view of the opened compressor test shell showing the compressor instrumented with different pressure and temperature transducers is shown in **Fig. 7**

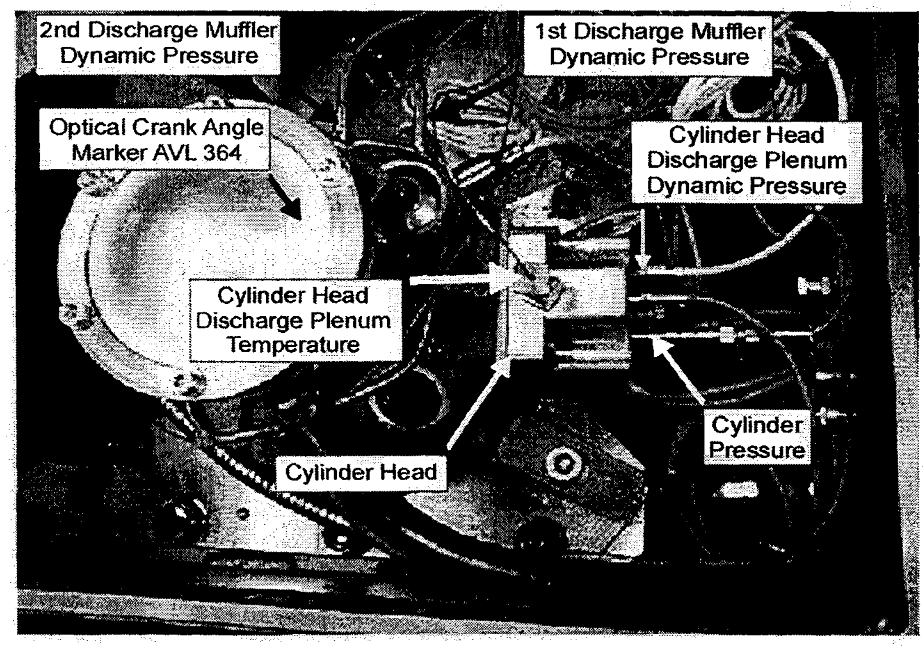

Fig. 7 Compressor Instrumented for Dynamic Pressure and Performance Measurements

<u>4.1 Cylinder Pressure Transducer Arrangement</u>

Special efforts were undertaken to design a cylinder pressure arrangement which introduces a minimum of additional cylinder dead volume. It was decided to arrange the cylinder pressure transducer through the cylinder head and screw it into the valve plate, **Fig. 8**. For this purpose the AVL GM11S piezoelectric pressure transducer was selected due to it's design features M 5 x 0.5 mm thread and long body. A special cylinder head was designed to host, beside the cylinder pressure transducer, also dynamic / static pressure and temperature transducers for the cylinder head discharge plenum. A special valve plate was also designed to accommodate the cylinder pressure transducer. The cylinder dead volume was increased by only 9 % due to the cylinder pressure transducer arrangement.

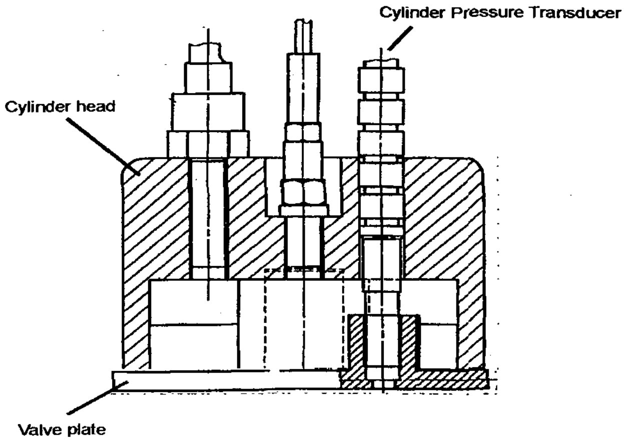

Fig. 8 Cylinder Pressure Transducer Arrangement

4.2 Dynamic Pressure Measurement Results

The dynamic pressures were measured successfully along with the other typical characteristics measured on the refrigeration compressor test bed such as static pressures, temperatures, total electrical power and refrigerant flow. Dynamic pressures for several suction and discharge valve variants as well as for different dead volume variants were recorded as part of the measurement program. For creating the proper basis for the one dimensional thermodynamic cycle code calibration, measurements with the cylinder dead volume set to the same level as for the valve motion visualisation were also carried out. The relative dynamic pressures recorded by the piezoelectric pressure transducers were adjusted to the absolute pressure level relying on the static pressure measurements. In **Fig. 9** a set of typical dynamic pressure measurement results are shown

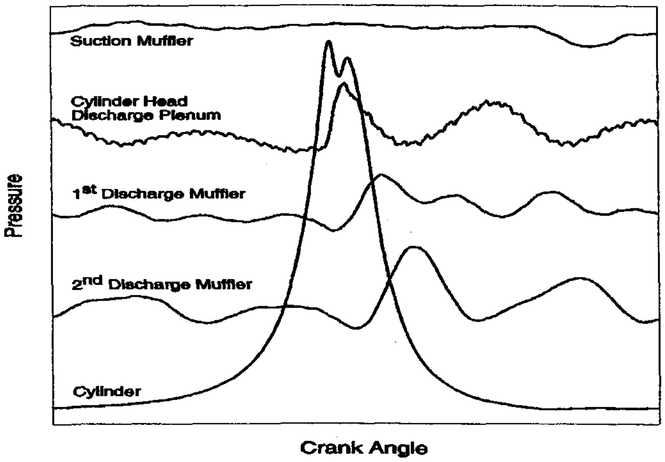

Fig. 9 Dynamic Pressure Measurement Results

5. THERMODYNAMIC COMPRESSOR CYCLE CALCULATIONS USING THE AVL BOOST CODE

After the results of the experimental investigations, valve motion visualisation and refrigerant dynamic pressure measurements, were completed the analytical part of the work was carried out. The aim of the calculation was to prove the potential of the AVL BOOST code to simulate the compressor cycle and the phenomena taking place in the suction and discharge systems.

5.1 Calculation Code Description

AVL BOOST calculates the unsteady 1-dimensional gas flows in the suction and discharge systems in addition to the in-cylinder conditions. This is achieved by solving the appropriate set of coupled non-linear differential equations using a Godunov-type finite volume scheme with ENO-reconstruction of the flow field. The pipes are divided into cells and the flows of mass, momentum and energy from one cell to the other are calculated by a Riemann solver. The effects of wall friction, heat transfer and varying cross sections of the pipes are considered by using source terms in the differential equations. The gas properties at any location are determined by solving the conservation laws for unburned fuel, combustion products and air. The flow losses at the pipe attachments are treated as quasi-steady. Empirically determined catalogue values of pressure losses determined experimentally for the most common boundary elements, are used where appropriate. The calculations are initiated with user specified initial conditions in the system and they are iterated until the solutions of subsequent cycles converge. The calculation model is constructed by using a set of elements available in the BOOST pre-processor. The elements available comprise among others: system boundaries, pipes, plenums, variable volume plenums, cylinders, junctions and linking elements to a 3D CFD AVL FIRE simulation domain. The analysis of the results is assisted by an interactive post-processor.

5.2 Thermodynamic Cycle Calculations For The GLY75AVL Compressor

First the calculation model of the GLY75AVL compressor was constructed, **Fig. 10** The model starts with the system boundary SB1 which simulates the condition inside the compressor test shell. The refrigerant is aspirated through the suction muffler modelled by the pipes 1, 2 and the plenum Pl1, passes the suction valve simulated by the check valve CV1 and enters into the cylinder simulated by the variable plenum Pl1. The pipe 10 simulates the refrigerant blow by between piston and cylinder liner. On the discharge side the check valve CV2 simulates the discharge valve, plenum Pl2 models the discharge plenum inside the cylinder head, while plenums Pl3 and Pl4 stand for the 1st and 2nd discharge muffler, respectively. Further downstream the internal discharge tube, pipe 8, and external discharge tube, pipe 9, lead the refrigerant into the refrigerant circuit simulated by the system boundary SB2. The compressor suction and discharge valves are simulated by the check valve element of the calculation code. The flow through the check valve in is based on the energy and continuity equations and the formulae for the isentropic change of state. The valve lift is calculated using a spring-damper-mass model. The gas properties of the R134a refrigerant were built into the calculation code. The calculations were performed for the suction pressure of 1.148 bar. The results of the experimental investigation were used to validate the calculation results. A good correlation of the calculated valve lift was achieved, **Fig. 11**.

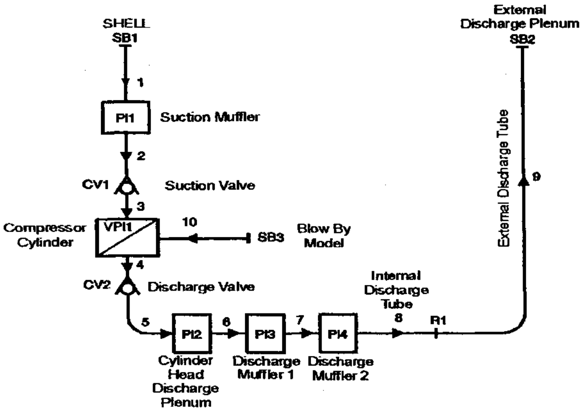

Fig. 10 GLY75AVL Calculation Model for Different Suction Pressure Levels

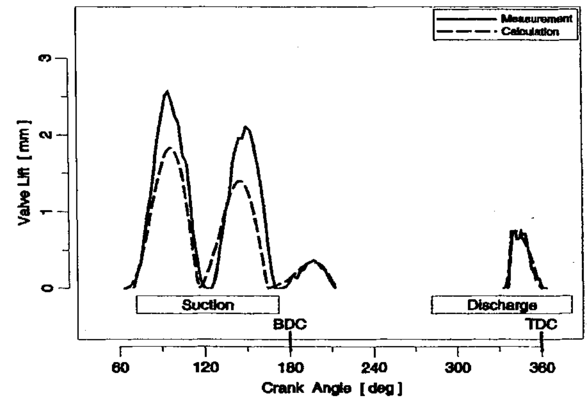

Fig. 11 Calculated and Measured Valve Lift Suction Valve Design Comparison

The comparison of measured and calculated pressure histories in the cylinder, suction muffler and cylinder head discharge plenum was also satisfactory, **Fig. 12** Generally the thermodynamic cycle calculation results were encouraging.

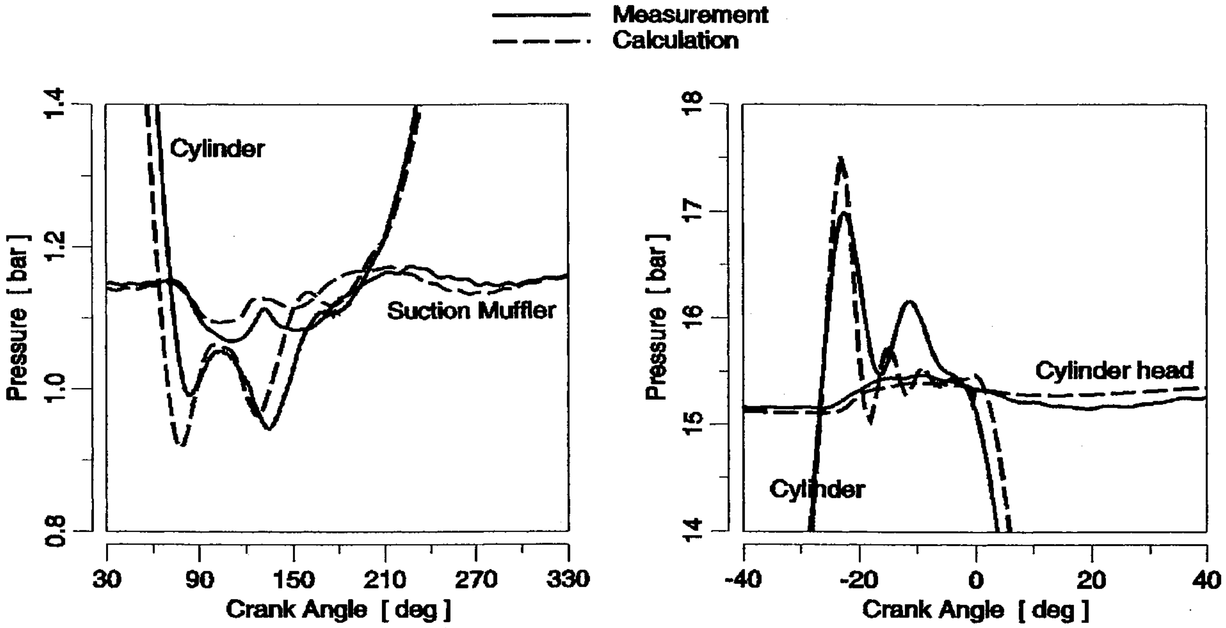

Fig. 12 Calculated and Measured Pressures

During the calculation model calibration process parameters of importance to a successful simulation result were identified. Modelling the right amount of blow by between piston and cylinder liner influences the refrigerant flow and thus, the compressor performance. The heating of the refrigerant in the suction muffler and in the suction hole of the valve plate has to be simulated carefully in order to calculate realistic pressure and temperature conditions upstream and downstream the suction valve, and as a result, generate a realistic suction valve lift prediction.

6. CONCLUSIONS

Experimental and analytical investigations performed for the hermetic compressor GLY75AVL used for household refrigeration showed promising results. A dedicated method and system to visualise reed valve motion was developed and successfully applied under challenging circumstances set by the hermetic compressor operation and the reduced size of the compressor investigated. The quality of the video valve lift videos produces is good; the valve opening and closing events, as well as the valve behaviour can be clearly seen. A picture superposition procedure was used to quantify the valve lift.

The compressor was prepared and instrumented for dynamic pressure measurement. The cylinder pressure was recorded using a transducer mounted frontal to the cylinder. This enabled to minimise the additional dead volume introduced by the cylinder pressure transducer installation.

The valve motion and the refrigerant dynamic pressure were recorded at several compressor locations for different valve design variants and at different evaporating temperatures (suction pressures).

Finally thermodynamic compressor cycle calculations were performed. The potential of the calculation code used to simulate the in-compressor processes was proven. A satisfactory calculation to measurement correlation could be achieved.