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A TECHNICAL NOTE ON THE EFFECTS OF SUCTION CHAMBER AND CELL INTERACTION ON THE SUCTION CHARACTERISTICS OF A ROTARY VANE COMPRESSOR

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ABSTRACT

In most sliding vane air compressors, the angular span of the suction port is usually larger than that of an individual cell. Hence two or more cells may communicate simultaneously with the suction plenum chamber during the suction process. Because of this, the suction process in this type of compressor is a continuous process and pulsation effects are small compared to those found in reciprocating compressors. This paper illustrates a theoretical study of the suction characteristics of a sliding vane compressor by accounting for the effects of the interaction between the "cell-in Question" and its neighbouring cells (during the suction process) as well as the suction plenum chamber. The variations of pressure, temperature and air mass flow into and/or out of each of the neighbouring cells and the suction chamber during the suction process are shown and discussed together with those of the "cell-in question".

INTRODUCTION

In the construction of certain sliding vane compressors, a suction plenum chamber is frequently located between an air intake valve and the suction port as shown in Figure 1.

The suction plenum of such a compressor is sometimes called the air intake valve chamber since it is the place where the intake valve is housed. The existence of an intake valve in the suction plenum does not improve the suction characteristic but provides a non-return valve mechanism when the compressor is stopped. It prevents high pressure fluid from escaping through the low pressure side of the machine via the suction port. In some machines this valve acts as part of a hydraulically actuated servo control system which closes the air intake port when the compressor is running off load.

A previous attempt [1] to model this type of machine, showed that a simple model which assumed that the suction plenum was volumetrically large compared to the active cell volume, gave good overall agreement between predicted and measured results. When modelling the suction process without considering the existence of a suction plenum, the nominal suction conditions were taken as constant and set equal to atmospheric conditions. This paper shows the influence of the presence of the suction plenum on the modelling results. It also shows the effects of cell interactions during the suction process.

Suction Characteristic

Any interaction between the cells influences the suction characteristic to some extent and depends mainly on the relative volume of the suction plenum and the active cells. In the following sections the influence of the air intake valve, the suction plenum and the interaction of the neighbouring cells during the suction process predicted by a theoretical model are discussed.

The analysis which follows applies to an existing compressor model or to machines with a similar configuration. A schematic diagram of the machine is shown in Figure 2 which illustrates the arrangement between suction valve, suction plenum and the compressor working space. Point 'A' and point 'B' represent the suction port opening and closing position respectively.

In the present study of an eight vane machine the cell angle is i.e. 45° and the circumferential span of the suction port is 79°. Close examination of the suction port dimensions given above shows that during the suction process a maximum of three cells and at least two cells may communicate simultaneously with the suction plenum. This means that in addition to the cell in question, there is at least one other cell which is also communicating with the suction plenum. The existence of these neighbouring cells and the interaction between them during the suction process is termed cell interaction. To model the compressor as a whole and its suction plenum in particular, interaction during the suction process must be considered.

Theoretical Model of The Suction Plenum

The existing suction model formed part of the mathematical model describing the complete compressor and used the following criteria:-

a) The process occurring in the suction plenum was assumed to be adiabatic, i.e. $Q=0$.

b) The plenum chamber has a fixed volume, i.e. $dV_p = 0$ and means that the work done term associated with the plenum is zero i.e. $W=0$.

c) For the present study, perfect sealing was assumed to exist between the plenum and the outside world, i.e. no leakage flows out of or into the plenum. This assumption is justified because the pressure difference between the suction plenum and its surrounding is small.

d) A quasi steady process is assumed for the flow through the suction plenum and means that at any particular instant the unsteady flow through the suction plenum can be treated as steady.

e) The flows into and out of the plenum chamber are assumed to behave as one dimensional isentropic flows through an orifice. An effective flow area is introduced by using a discharge coefficient with the area calculated from the actual geometry of the port.

f) Air behaves as ideal gas.

Figure 3 shows a control volume which was used to represent the suction plenum of the compressor. From the above assumptions, the primary activity which occurs is mass flow into and out of the control volume. There is massflow through the air intake valve m_i, mass flow out of the suction plenum through the suction port m_o into the cell in question, and mass flow caused by cell interaction effects m_{ci}.

Considering the control volume as an entity, from the Law of Conservation of Energy the following equation may be obtained:-

$$\frac{dQ}{dt}+\Sigma\left(\frac{dm}{dt}C_pT\right)_i=\frac{dW}{dt}+\Sigma\left(\frac{dm}{dt}C_pT\right)_o+\frac{d}{dt}(mu)_p \qquad \ldots(1)$$

This equation is solved simultaneously with the mass conservation equation i.e.:-

$$dm_i-dm_o=dm_p \qquad \ldots(2)$$

Solving equations (1) and (2) simultaneously for a fixed volume plenum chamber together with the equation of state for an ideal gas and accounting for the effects of cell interaction yields,

$$\frac{dP_p}{dt}=\frac{\gamma RT_i}{V}\frac{dm_i}{dt}-\frac{\gamma RT_p}{V}\frac{dm_o}{dt}\pm\frac{\gamma R}{V}\left(\Sigma\left(T_T\frac{dm_T}{dt}\right)+\Sigma\left(T_L\frac{dm_L}{dt}\right)\right) \qquad ...(3)$$

$$\frac{dT_p}{dt}=\frac{T_p}{P_p}\frac{dP_p}{dt}-\frac{RT_p^2}{P_p V_p}\frac{dm_p}{dt} \qquad ...(4)$$

$$\left(\frac{dm_p}{dt}\right)=\frac{dm_i}{dt}-\frac{dm_o}{dt}\pm\Sigma\frac{dm_T}{dt}\pm\Sigma\frac{dm_L}{dt} \qquad ...(5)$$

i) Suffix T denotes properties of a group of cells which is at the trailing side of the cell in question with respect to the direction of rotor rotation and which communicate with the suction plenum during the suction process.

ii) Suffix L denotes properties of a group of cells which is at the leading side of the cell in question with respect to the direction of rotor rotation and which communicate with the suction plenum during the suction process.

iii) Suffices i and o denote massflow and the properties of the air entering and leaving the cell in question only.

FURTHER SIMULATION ASSUMPTIONS

Calculations were performed for the following conditions:-

i) With the air intake non return valve free to move instantaneously, depending on the pressure differential across the valve, i.e. If $P_{ATM} > P_p$ the valve would be fully open where for $P_p > P_{ATM}$ the valve would be closed.

ii) Ignoring cell interaction effects.

iii) Accounting for cell interaction effects.

The initial conditions in the suction plenum were taken as T= 25°C and P = 1.01325 bar (760 mmHg) with the intake valve closed.
Effective air intake valve flow area $= C_d(\pi/4)((d_v)^2-(d_r)^2)$
where $C_d = 0.6$, $d_v = 32$mm, $d_r = 10$mm.
The atmospheric condition was taken as at $T_{ATM} = 20$°C and $P_{ATM} = 1.01325$ bar, where C_d is the discharge coefficient, and d_v and d_r are the valve port and the valve rod diameter respectively.

Calculations were performed for various suction plenum chamber volumes, ranging from 1000 mm³ to 8000 mm³.

DISCUSSION OF RESULTS

Plenum Chamber Conditions

Two distinct sets of calculations were performed. The first excluded interaction of neighbouring cells and the second took the effects of cell interaction into consideration.

a) Plenum Pressure And Temperature Variation

Figure 4 shows the comparison of variations in the plenum pressure during the suction process, both neglecting and accounting for the effects of the cell interaction. When the plenum chamber is interacting only with the cell in question, the condition in the plenum chamber is greatly dependent on the variation of the size of the suction cell, where the latter is a function of the cell angular position. The sudden decrease in the pressure of the plenum chamber to a value of 100800 N/m², is caused by mass flow out of the chamber into the cell, when the suction port is first uncovered. This causes the pressure in the plenum chamber to drop to a level which is lower than the atmospheric pressure and hence causes the intake valve to open and permits the induction of air from the atmosphere into the plenum chamber through the air intake valve. This process causes the plenum chamber pressure to recover. As the mass flow into the cell and the mass flow into the plenum chamber are of a similar magnitude, the plenum pressure stays reasonably constant. This is shown in the later stage of the suction process.

A more realistic consideration of the suction process accounts for the interactions between the plenum chamber, the neighbouring cells and the cell-in-question.

Because the volume of the plenum chamber is fixed, and also because of the assumption of an adiabatic process occurring in the plenum chamber, the chamber pressure is primarily influenced by the **incoming** and the **outgoing** mass flow. The temperature of region from which a mass flow originates also has an influence although in the present study this temperature influence was discounted.

The pressure oscillations are caused by the rate of change of the mass in the plenum chamber i.e. the difference between the mass flow into and out of the plenum chamber. It is shown in figure 4 that the calculated plenum pressure which takes into account cell interaction is always lower than that in the case without cell interaction. This effect is caused by the additional mass flow into the neighbouring cells.

The temperature variation in the suction plenum chamber is shown in figure 5. It may be seen that the temperature variation is very small, (less than 0.4°C whereas the corresponding pressure variation is approximately 800 N/m^2 (~8cmH_2O). Figure 5 shows that the plenum temperature variation accounting for cell interaction effects oscillates about the plenum temperature with no cell interaction effects. By comparing figures 4 and 5, it may be seen that the temperature variation is in phase with the pressure variation. The relative magnitude of the two governing terms in the rate of change of temperature equation, i.e. the pressure and mass flow terms controls the plenum chamber temperature variation as follows, i.e.

$$\frac{dT}{dt}=\frac{T}{P}\frac{dP}{dt}-\frac{T}{M}\frac{dM}{dt}$$

$$dT=T\left(\frac{dP}{P}-\frac{dM}{M}\right)$$

if $dM/M<dP/P$ then dT/T is in phase with dP/P whilst if $dM/M>dP/P$ then the reverse is also true.

b) Mass Flowrates

Figure 6 shows the comparison of the variation of the mass flowrate into the cell in question both with and without cell interaction. It is clearly shown that, as the mass flow into the cell reaches its maximum value, the plenum chamber experiences the greatest pressure and temperature drop. The reason that the mass flowrate into the cell rises quickly at the beginning of the suction process is attributable to the high pressure difference across the suction port and an increasing flow area at the beginning of the suction process. The mass flowrate stays reasonably constant as the cell pressure approaches the plenum chamber pressure (and the flow area approaches a constant value). The cell mass flowrate reduces at the end of the suction process because the cell pressure very nearly equals the plenum pressure and the suction port area approaches zero as the suction port is fully covered. When accounting for cell interaction effects, it may be seen that there is a small fluctuation in mass flow at the leading vane position between 120°–140°. This would be attributable to the reduction in plenum pressure shown in Figure 4 as additional mass enters the cell adjacent to the cell in question.

Figure 7 shows the variation of mass flowrate through the air intake valve, compared to all other components of mass flow through the suction port. It may be seen that the mass flowrate term for the air intake valve is always positive which means that the valve is always open, because the plenum pressure is always less than the atmospheric pressure. It may be noticed that the mass flowrate through the air intake valve is higher than any other individual mass flowrate.

This is because the inflow through the air intake valve provides the total mass flow through the suction port. Figure 8 shows the terminologies used to describe the various mass flowrates schematically.

Figure 9 shows the variation of the mass in the plenum chamber (i.e. the sum of the mass flow out of the plenum chamber into the compressor cells minus the mass flow into the plenum chamber through the air intake valve) together with variations of the plenum pressure and plenum temperature plotted against the leading vane position of the reference cell during part of the compressor's operational cycle.

It is clearly shown that the rate of change of plenum pressure (dP/dt) is influenced by the variation of the mass flow of the chamber.

Figures 10 and 11 show the comparison of cell pressure and cell temperature with and without cell interaction. Figure 12 shows the associated comparison of the pressure volume diagram. It may be seen that there is no significant difference as far as the cell properties and the work done are concerned. It was also noticed that at least three times the computational time was required to incorporate the existence of a suction plenum into the present modelling study. The inclusion of the plenum chamber in the calculation may be considered as a big effort with but a small benefit. For many purposes the suction plenum chamber volume may be considered to be large compared with the cell volume and its presence neglected. However for the compressor which was the subject of the present study it was also noticed that a plenum chamber volume of less than 1000 mm^3 may be considered as small, and the calculations needed a very small step size to achieve convergence.

CONCLUSION

It is concluded from the present study which formed a part of K.T. Ooi's doctoral work (3) that cell interaction during the suction process produces only slight effects on the suction plenum pressure, the associated effects on the plenum temperature and mass flow are very small. The size of the plenum chamber in the present study was relatively large compared to the active cell volume and had negligible influence on compressor modelling results.

ACKNOWLEDGEMENT

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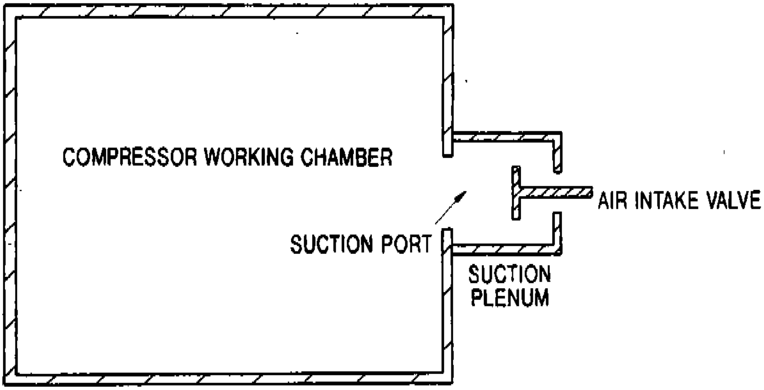


FIGURE 1. SUCTION PLENUM AND WORKING CHAMBER.

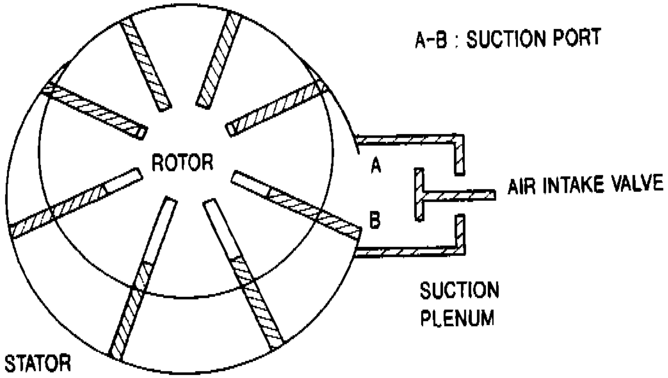


FIGURE 2. SCHEMATIC ARRANGEMENT OF A ROTARY COMPRESSOR WITH AN INLET SUCTION PLENUM

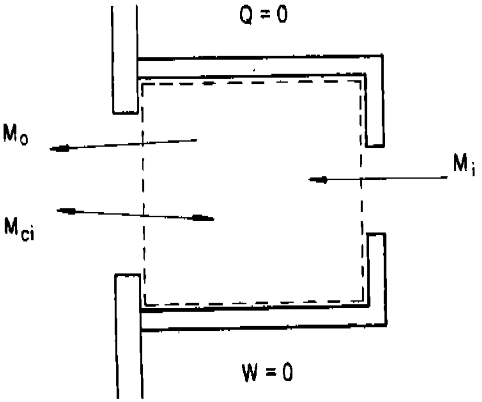


FIGURE 3. SUCTION PLENUM CONTROL VOLUME

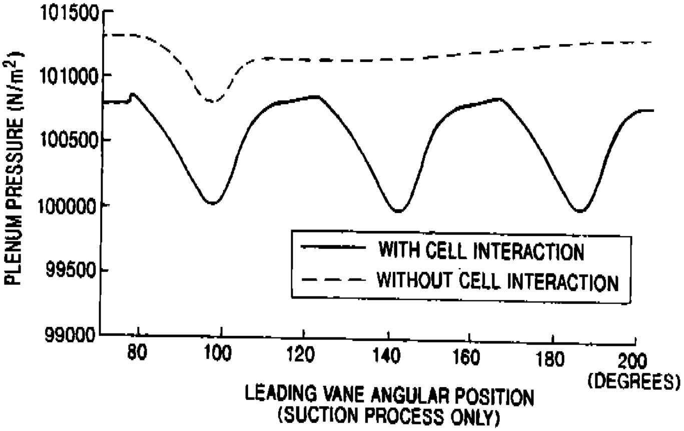


FIGURE 4. VARIATION OF PLENUM CHAMBER PRESSURE

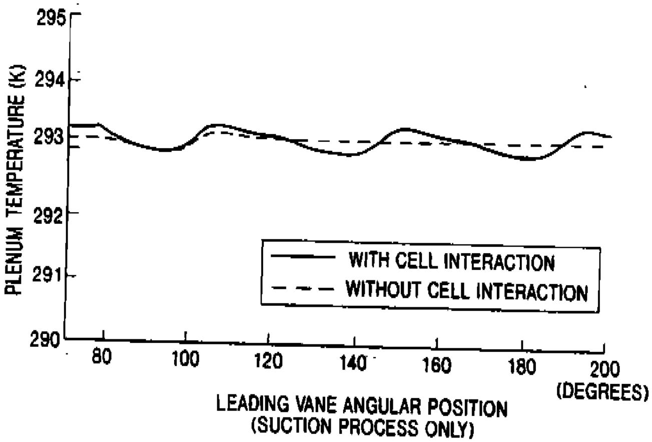


FIGURE 5. VARIATION OF PLENUM CHAMBER TEMPERATURE

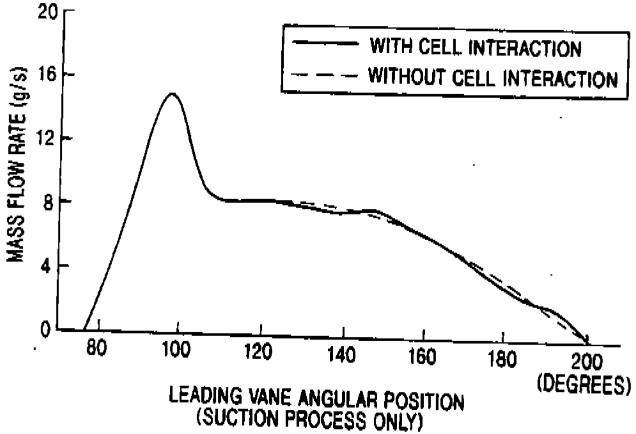


FIGURE 6. VARIATION OF MASS FLOW RATE INTO CELL IN QUESTION

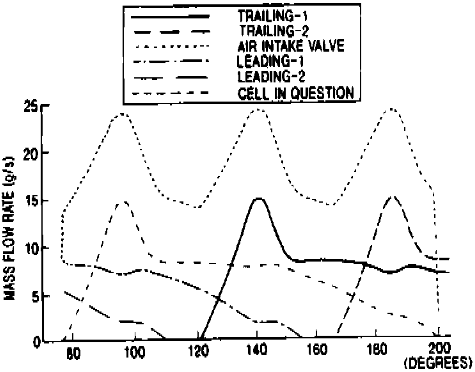
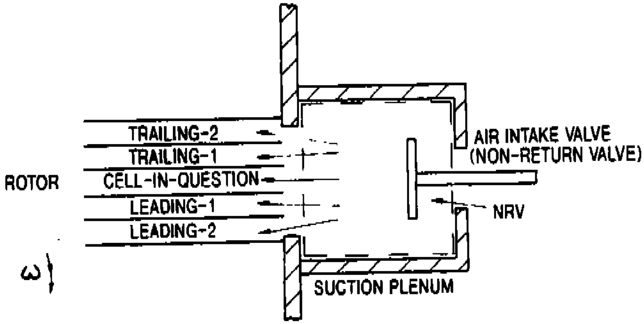


FIGURE 7. VARIATION OF MASS FLOW RATE TO VARIOUS CELLS DURING SUCTION PROCESS



NOTE: ARROWS SHOW POSITIVE MASS FLOW DIRECTION. (IN THE REAL COMPRESSOR THERE WILL BE AT MOST 3 CELLS COMMUNICATING SIMULTANEOUSLY WITH THE SUCTION CHAMBER.)

FIGURE 8. MASS FLOW TERMINOLOGIES.

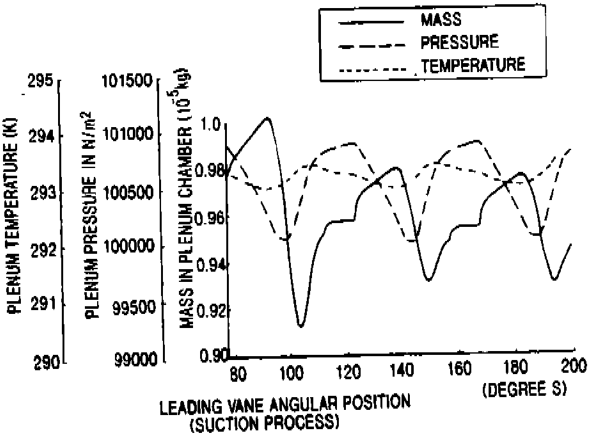


FIGURE 9. VARIATION OF PLENUM CHAMBER PROPERTIES.

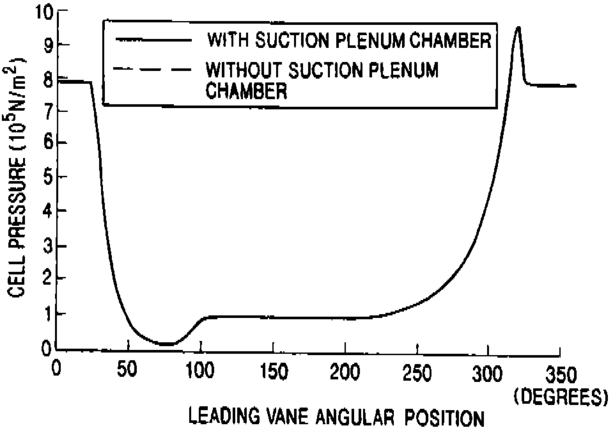


FIGURE 10. PREDICTED CELL PRESSURE WITH AND WITHOUT PLENUM CHAMBER

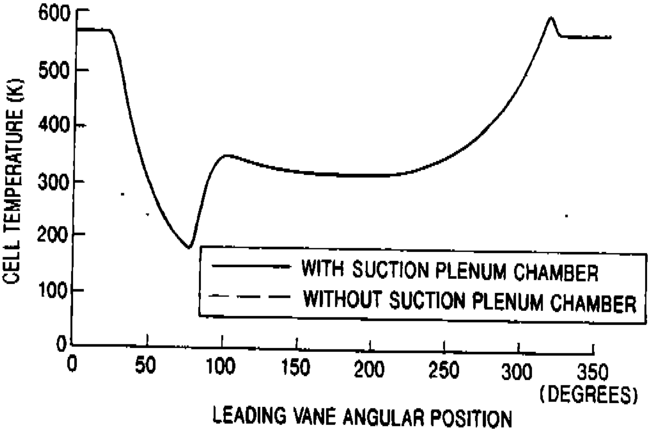


FIGURE 11. PREDICTED CELL TEMPERATURE WITH AND WITHOUT PLENUM CHAMBER

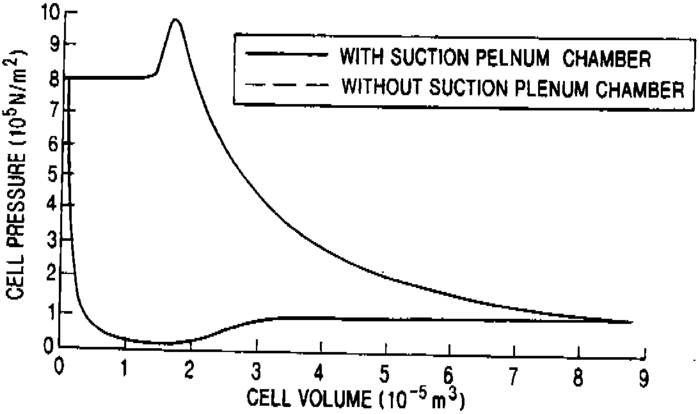


FIGURE 12. PREDICTED P-V DIAGRAM WITH AND WITHOUT PLENUM CHAMBER