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FAST RESPONSE TEMPERATURE MEASUREMENTS IN A RECIPROCATING COMPRESSOR

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ABSTRACT

Mathematical modeling of the dynamic processes in a compressor involves a knowledge of the various forms of energy exchange occurring in the system. Heat transfer to and from the gas is one such. Any detailed modeling of the heat transfer process would require a detailed knowledge of the temperature variations resolved to temporal scales at least as fine as the finest generated by the dynamics of the valves and their interaction with the cylinder and piping. This paper presents measurements of gas temperature inside the cylinder and valve chambers made with a new type of thermocouple sensor which can meet the fast response requirements. The measurements were used to predict the effect of suction gas heating on capacity loss which agreed quite well with direct capacity loss measurements.

INTRODUCTION

The ever increasing demand for improving energy efficiency and pollution control has fueled lot of research on the understanding of the dynamic processes in machinery including reciprocating compressors and its application to analytical modeling. In reciprocating compressors, until recently , the heat transfer process had assumed a back burner role. This was partly because of the notion that heat transfer has very little impact on the performance of a reciprocating compressor and partly due to the difficulty in modeling the complex heat transfer processes. Even determination by experiment is also not an easy task, since it is very difficult to isolate its effects.

Most of the work on heat transfer effects have been done in the area of refrigeration compressors. Meyer and Thompson [1] have studied heat transfer effects on the performance of refrigeration compressors by using a steady state modeling of the complete system. They particularly studied the impact of inlet system design on heat transfer effects. The comparison of the results of their model with experimental data indicated reasonable agreement and suggested that the discrepancies could perhaps be reduced by considering the unsteadiness in the heat transfer process occurring inside the cylinder. Pandeya and Soedel [2] have derived a simple relationship for the change in mass flow rate expressed as a function of the magnitude of suction gas heating using thermodynamic principles. Adair, Qvale and Pearson [3] have provided a correlation for the instantaneous heat transfer across the cylinder based on dimensionless quantities with constants derived from their experimental data. Jacobs [4] has reported measurements of the important losses in a compressor. In addition, he observed the benefit of cooling of the suction gas on volumetric efficiency increase. He also indicated that a suction gas heating of 10°F would reduce the volumetric efficiency by approximately 2 %. On the other hand, Brok, Touber and Vander Meer [5] provided credence to the conflicting opinion about the extent of influence of heat transfer on volumetric efficiency decrease by suggesting that the impact (was only 2.5 % for the compressor they modeled) is only nominal.

Lee and Smith [6] have measured instantaneous temperature inside the cylinder in order to understand the heat transfer mechanism and its impact on volumetric efficiency loss. Hanjalic and Stosic [7] have also made measurements of instantaneous temperature and pressure inside the cylinder in order to understand the dynamic processes occurring inside the cylinder and to develop a mathematical model for simulating the compressor for aiding the designer. Gerlach and Berry [8] have assessed heat transfer losses by force fitting experimentally measured discharge temperature to their mathematical simulation of the compressor. The capacity loss based on their heat transfer estimate agreed quite well with their direct measurements, thus giving credence to their heat transfer model. They also obtained reasonable agreement between their predicted and measured variation of cylinder gas temperature over the cycle. Of all the reported temperature measurements in a compressor, Lee and Smith appear to be the only ones who have used a sensor with a very fast response (1 msec.). Their probe design which is similar to the commercially available bare wire thermocouple sensor with an exposed loop of the bare wire thermocouple is difficult to make and does not appear to be rugged. In addition, since the thermocouple bead is only 0.5 mm away from its supporting tube, it is likely to disturb the flow. Commercially available thermocouple probes, although more rugged are more sluggish and do not have a response faster than 10 - 20 msec. The other techniques which can provide the fast response required, like the optical techniques using laser induced fluorescence, are not easily adaptable to measurement inside a compressor and also involve sophisticated and expensive instrumentation. All these problems were overcome by designing a new thermocouple probe similar to the hot-wire probe and was successfully employed in this investigation for making temperature measurements.

This paper reports measurements of instantaneous temperatures inside the cylinder and suction and discharge valve chambers of the first stage of a two stage, double acting compressor. Other measurements for assessing the compressor performance including the p-v diagram, heat rejection to cooling water and compressor capacity were also taken. Since the main objective was to assess the effect of suction gas heating on capacity loss, the capacity was carefully monitored right from the instant of time the compressor was started from cold condition. The measurement of the total suction gas heating together with an assessed variation of capacity as a function of suction gas heating enabled the estimation of total capacity loss due to suction gas heating. The results are compared with the expression given by Pandeya and Soedel [2] based on suction gas temperature increase alone.

PROBE DESIGN AND CONSTRUCTION

In addition to fast response, ease of fabrication, ruggedness and applicability for point measurement were some of the other considerations kept in mind during the design of the probe. To get that fast response, it was obvious that it should be of the exposed junction type. The commercially available ribbon type thermocouple, in addition to not being able to meet the response requirement is also not well suited for point measurements. Also, in a turbulent environment, the large drag forces might induce vibrations and even snap the wire. Using a round wire thermocouple in the form of a loop as done by Lee and Smith is difficult for construction, particularly if the wire diameter is reduced to 0.0005 in. for obtaining a faster response. Further, the loop need to be big enough to reduce disturbance to the flow near the bead. But making it bigger makes it more fragile. To satisfy all these conflicting requirements, a new design similar to that of the hot-wire probe was conceived.

The tips of two 0.015 in. diameter wires of Chromel and Constantan served both as sensor supports as well as lead wires for the thermocouple (see fig. 1). These leads were passed through the two holes of a 1/16 in. diameter ceramic tube (approximately 2.25

ins. long) and glued to it using OMEGA CC high temperature cement. The exposed lead wires on the other side were covered with insulating sleeves which can withstand temperatures up to 600°F. The ceramic tube itself was passed through a 0.25 in. outside diameter stainless steel tube and glued to it using the high temperature cement. A 0.0005 in. diameter Chromel-Constantan bare wire thermocouple was spot welded to the tips of the supports, taking care to keep the bead at the middle and welding the Chromel wire to the Chromel support and the Constantan wire to the Constantan support. This unique construction similar to a hot-wire probe helped retain the complete fast response (the response is expected to be better than the probe designed by Lee and Smith which had a time constant of 1 msec.) capabilities of the bare wire thermocouple, while keeping errors due to conduction and radiation very small.

INSTRUMENTATION

The measurements were done in a two stage, single cylinder, double acting compressor running at approximately 900 rpm. The suction pressure was atmospheric and the discharge pressure was 110 psig. All measurements were mainly confined to the head end of the first stage cylinder.

Chromel-Constantan was chosen as the thermocouple material because of its high sensitivity. The voltage output by the thermocouple was directly recorded using a 4 channel NICOLET oscilloscope using 3mv/cm and 500 sec/point sensitivities which were good enough to discern the variations over the cycle clearly. Thus the need for using additional signal conditioning instrumentation which also adds noise was avoided. The compensation for the cold junction (both of which were exposed to the room temperature) was done by adding the room temperature which was monitored. The oscilloscope sweep was triggered by the signal from an optical encoder which was synchronized to occur at the top dead center.

Two probes were installed inside the cylinder, one near the center of the head and the other at the exit of the suction valve. Probes were also installed in the suction and discharge valve chambers just above the valve. Signals from 4 transducers at a time were recorded simultaneously on a floppy disc. Temperatures at various points along the flow path were also monitored using OMEGA J type thermocouples. The capacity was monitored by measuring the pressure drop across an orifice installed in the inlet pipe. The p-v card was recorded using a PFM 2000 cycle analyzer.

RESULTS AND DISCUSSION

Figure (2) shows the p-v and t-v cards. One can observe that the cylinder gas temperature variation follows a pattern similar to that of the pressure. Figures (3) - (5) show the effect of compressor heating up on the cylinder gas (at the center of the head) and suction and discharge valve chamber temperatures. All of them showed a significant increase in temperature as the compressor heated up. Also, the two independent samples shown for each of the parameters showed good agreement indicating that there was very little cycle to cycle variation. One can observe from the simultaneous traces of fig. (6) that the gas heated up significantly (approximately 50°F) as it entered the cylinder through the suction valve and inside the cylinder itself during the suction stroke. Thus at the end of the experiment, out of the total suction gas heating of 66°F, most of it occurred inside the cylinder with only a small part occurring in the suction pipe and cylinder passages. Figure (6) also shows the effect of valve opening, which results in an increase in gas temperature in the valve chambers, followed by cooling due to the ingestion of cold suction gas in the case of the suction valve and mixing with the relatively cooler discharge gas in the case of the discharge valve. Figure (7) which shows simultaneous traces of gas temperature inside the cylinder at the center of the head and also near the suction valve indicates the extent of spatial nonuniformity in the temperature distribution inside the cylinder. This observation is in conformity with the earlier observations reported by Lee and Smith [6] and Adair et al [3].

One of the important objectives of temperature measurement inside the cylinder was to assess the extent of suction gas heating and then predict the capacity loss resulting from it. Capacity was also monitored to verify this prediction. Assessing suction gas heating based on gas temperature in the suction valve chamber will not give the total suction gas heating, because the in-cylinder regenerative heat transfer makes a significant contribution to the heating process. This was also demonstrated by the present experimental data taken after the compressor had attained thermal equilibrium, which showed approximately 42°F temperature raise in the suction valve and the cylinder compared to 24°F in the suction pipe and cylinder passages. Hence the trapped charge temperature inside the cylinder at the end of the suction stroke was used for assessing the total suction gas heating.

Figure (8) shows the capacity loss and fig. (9) the suction gas heating as a function of time. Both of them showed a very rapid rate of variation as the compressor started from cold condition and appeared to settle after about 3 hours of operation. The initial rate of loss of capacity was so rapid that it would have been erroneous to assume the first reading of capacity (which could only be taken after a few minutes of switching the compressor on) to represent the maximum value and basing the total capacity loss on that. The correct way would be to establish a functional relationship between the capacity loss and the suction gas heating and then use it to compute the capacity loss for the observed total suction gas temperature increase. Figure (10) shows such a graph of capacity loss against suction gas temperature increase which was derived from figs. (8) and (9). The correlation appears to be very closely linear.

Capacity loss was also computed from the measured total suction gas temperature increase using the expression given by Pandeya and Soedel [2]. Table (1) provides a comparison of the capacity loss obtained using the correlation shown in fig. (10) with that computed from suction gas heating and also from direct capacity monitoring compared with rated capacity. The agreement between all the three methods is very good.

The present experimental data has demonstrated the enormous influence of suction gas heating on compressor performance at least for the compressors of the type used in the experiment. It has also shown that because of the rapid rate of decrease of capacity during the start up and initial running of the compressor, the capacity measurement alone will not help in assessing the capacity loss due to suction gas heating. Simultaneous measurement of cylinder gas temperature and its use in establishing a correlation between suction gas heating and capacity loss is required for determining the capacity loss due to suction gas heating. The paper has thus underlined the importance of cylinder gas temperature measurement and demonstrated its measurement using a newly designed fast response thermocouple probe.

CONCLUSIONS

The investigation provided a new design for the thermocouple probe to meet the fast response characteristics and the ruggedness required for making temperature measurements inside the cylinder. The temperature measurements inside the cylinder not only indicated a significant spatial nonuniformity but also a large suction gas heating. The capacity loss due to suction gas heating obtained from the established correlation between suction gas temperature increase and capacity loss agreed very well with that computed from total suction gas temperature increase as well as direct monitoring of capacity.

Further work is in progress to make use of these temperature measurements for understanding the heat transfer mechanism and formulating a model enabling prediction of its effects on compressor performance.

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REFERENCES

1] Meyer, W.A. and Thompson, H.D., 'An Analytical Model of Heat Transfer to the Suction Gas in a Low-side Hermetic Refrigeration Compressor', Proceedings of the 1990 Purdue International Compressor Engineering Conference, West Lafayette, Indiana, pp. 898-907, 1990.

2] Pandeya, P. and Soedel, W., 'On Suction Gas Heating in Hermetic Compressors (A Technical Note)', Proceedings of the 1978 Purdue Compressor Technology Conference, July 1978, West Lafayette, Indiana, pp. 144-147, 1978.

3] Adair, R.P., Qvale, E.B. and Pearson, J.T., 'Instantaneous Heat Transfer to the Cylinder Wall in Reciprocating Compressors', Proceedings of the 1972 Purdue Compressor Technology Conference, West Lafayette, Indiana, pp. 521-526, 1972.

4] Jacobs, J.J., 'Analytical and Experimental Techniques for Evaluating Compressor Performance Losses', Proceedings of the 1976 Purdue Compressor Technology Conference, West Lafayette, Indiana, pp. 116-123, 1976.

5] Brok, S.W., Touber, S. and van der Meer, J.S., 'Modelling of Cylinder Heat Transfer - Large Effort, Little Effect?', Proceedings of the 1980 Purdue Compressor Technology Conference, West Lafayette, Indiana, pp. 43-50., 1980.

6] Lee, K. and Smith, J.L., 'Time Resolved Mass Flow Measurement for a Reciprocating Compressor', Proceedings of the 1980 Purdue Compressor Technology Conference, West Lafayette, Indiana, pp. 51-57.

7] Hanjalic, K. and Stosic, N., 'Some Aspects of Laboratory Testing and Computer Modelling of Two-stage Compressors with Inter and After Cooling', Proceedings of the Institution of Mechanical Engineers, London, pp. 11-19, 1978.

8] Gerlach, R.C. and Berry, R.A., 'Effect of Heat Transfer and Related Variables on Compressor Performance', Proceedings of the Fourth Annual Reciprocating Machinery Conference, San Antonio, Texas, 1989.

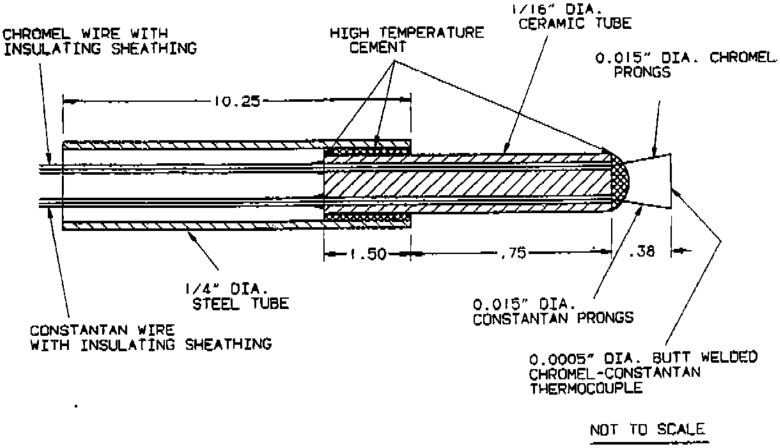

FIG.(1) PROBE FOR INSTANTANEOUS TEMPERATURE MEASUREMENT

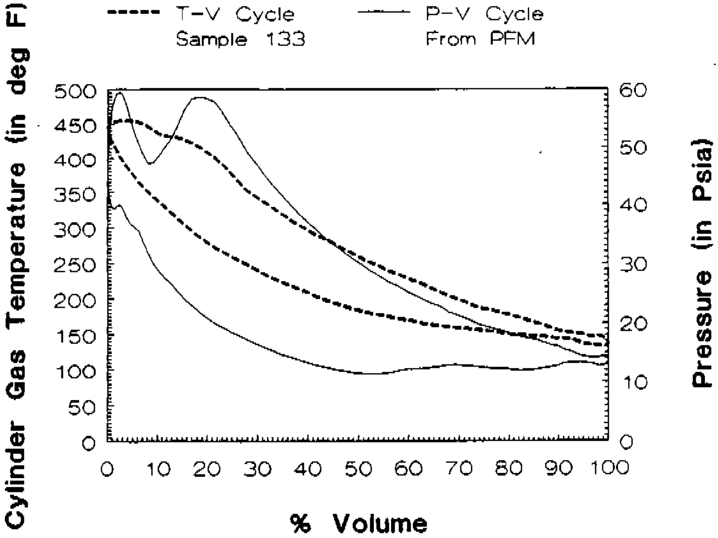

Fig. (2). Comparison of T-V and P-V Cycles after 3.5 Hours of Operation

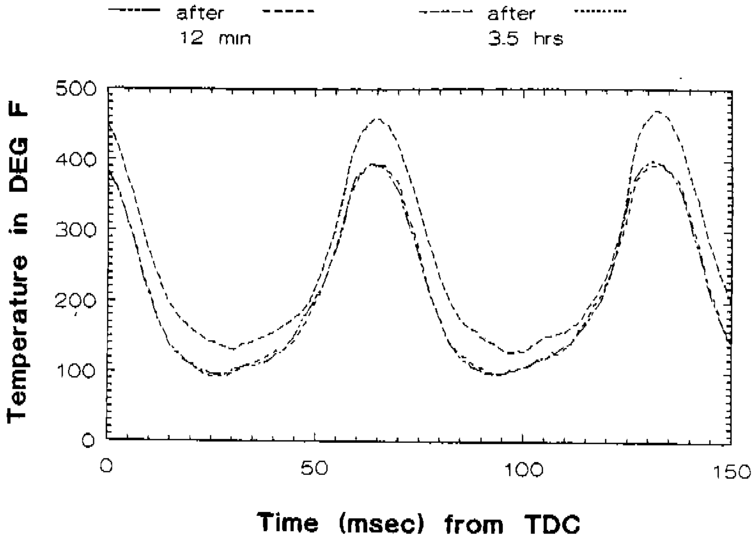

Fig. (3). Effect of Compressor Heating up on Cylinder Gas Temperature at the Center of Head

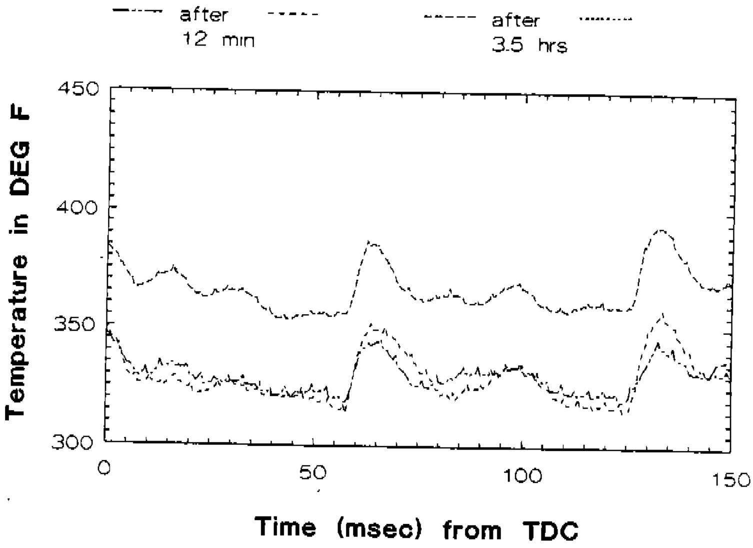

Fig. (4). Effect of Compressor Heating up on Discharge Valve Chamber Gas Temperature

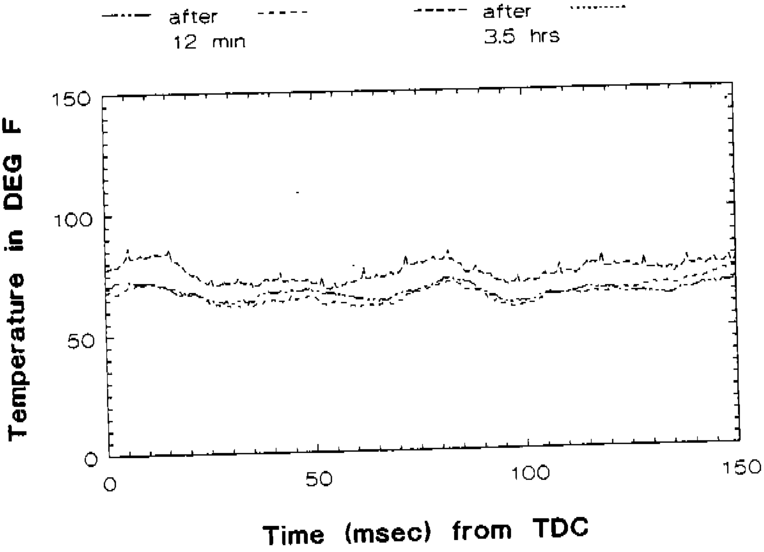

Fig. (5). **Effect of Compressor Heating up on Suction Valve Chamber Gas Temperature**

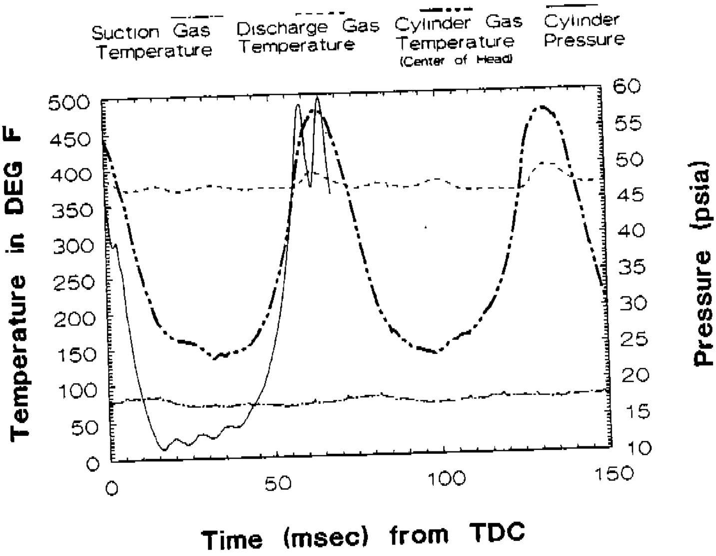

Fig. (6). **Simultaneous Traces of Gas Temperature and Pressure inside the Cylinder and Valve Chambers**

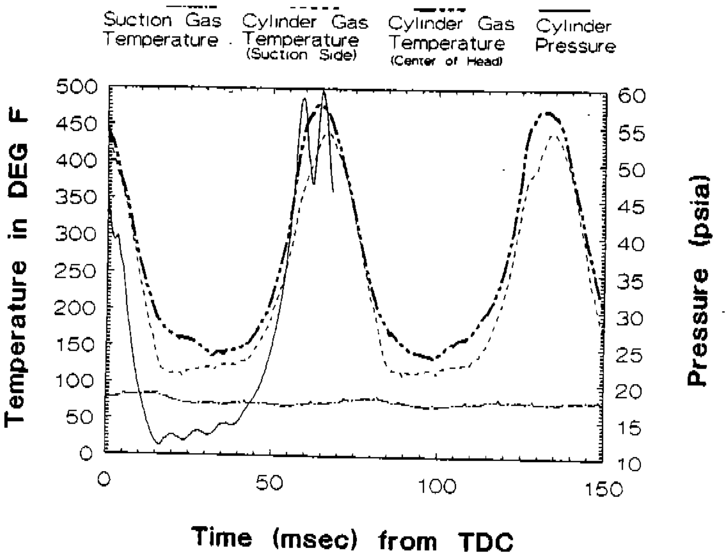

Fig. (7). Simultaneous Traces of Gas Temperature and Pressure inside the Cylinder and Valve Chambers

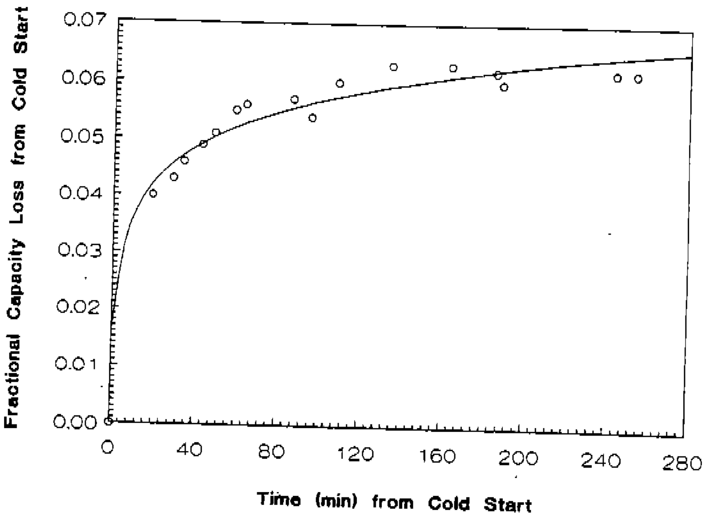

Fig. (8). Measured Capacity Loss Variation with Time

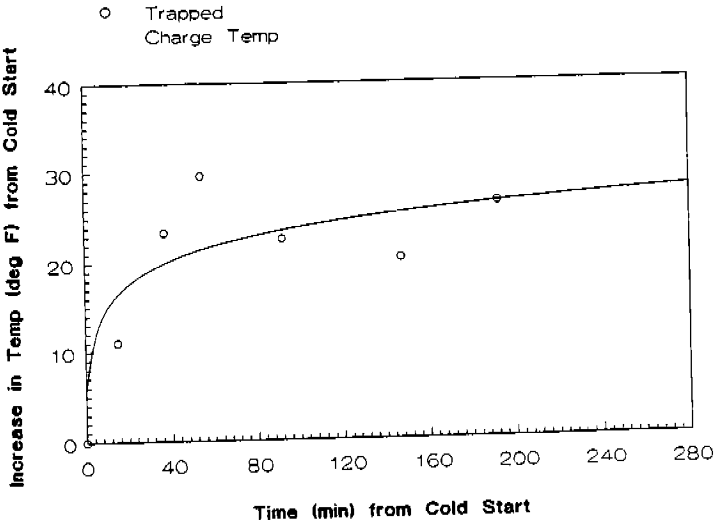

Fig. (9). Variation of Suction Gas Heating with Time

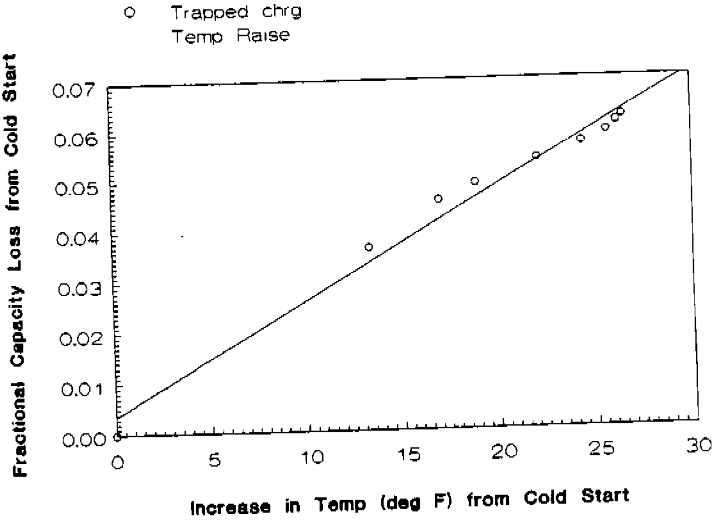

Fig. (10). Correlation of Capacity Loss with Suction Gas Heating

METHOD USED	CAPACITY LOSS	
	8 min After Start	At End of Expt
SUCTION GAS TEMPERATURE INCREASE	56 F	66 F
CAPACITY LOSS BASED ON RATED CAPACITY	12.6 %	17.1 %
FROM RESULTS OF MONITORING CAPACITY	12.9 %	15.2 %
CAPACITY LOSS BASED ON SUCTION GAS TEMPERATURE INCREASE	12.9 %	15 %

Table (1). Comparison of Measured and Computed Capacity Loss