MICRO-THERMOCOUPLE MEASUREMENT OF GAS TEMPERATURE TRANSIENTS IN A SMALL COMPRESSOR

André Morriesen, andrem@polo.ufsc.br
Cesar J. Deschamps, deschamps@polo.ufsc.br
POLO Research Laboratories for Emerging Technologies in Cooling and Thermophysics
Department of Mechanical Engineering
Federal University of Santa Catarina
88040-900, Florianópolis, SC, Brazil

Abstract. *In household refrigeration compressors, a significant portion of inefficiency is associated with superheating along the suction path. Despite its importance, a detailed thermal analysis of the suction system is difficult to obtain because of steep temperature transients in the refrigerant fluid along the operation cycle. Micro-thermocouples are small size and inexpensive sensors that can be used for temperature measurements without causing major interferences to the flow. In the present study, micro-thermocouple measurements were carried out in the suction system of a small reciprocating compressor to investigate gas superheating. In order to assess the micro-thermocouple adequacy for such analysis, measurements of temperature and velocity were also conducted with an anemometer system, composed by a single 5μm diameter tungsten wire sensor. Although possessing a lower time response when compared to the cold-wire sensor, the micro-thermocouple was seen to provide a reasonable description of the gas temperature transients.*

Keywords*: temperature transient, micro-thermocouple, cold-wire sensor*

1. INTRODUCTION

In household refrigeration compressors, a significant portion of the energy losses is associated with refrigerant superheating along the suction path. This useless superheating provokes a reduction in volumetric efficiency and an increase in compression work per unit mass. A detailed thermal analysis of the suction system can lead to a considerable improvement in its performance, mainly through the reduction of gas superheating. However, a complete analysis of the involved phenomena requires also data for gas temperature transients. This is a very difficult task because the time scale of such variations is similar to that of compressor valves.

The micro-thermocouple is a small size instrument capable of performing instantaneous measurements without causing major interference to the flow. Because there is no need to incorporate additional equipment for its operation and the possibility of using calibration curves available in literature, its implementation becomes attractive when compared with other measuring devices such as cold-wire anemometer. The current research cold-wire anemometry sensors have been developed to measure rapid fluctuations in temperature in a flow, allowing assess their turbulent quantities. Their sensitivity to temperature is much higher than the micro-thermocouple, however, requires special equipment to operate the probe and introduce greater perturbation to the flow than the micro-thermocouple.

Looking at the applicability of the micro-thermocouple, Prasad (1992) built a 12.7μm diameter chromel-constantan wire thermocouple especially designed for temperature measurements in a two stages, double acting, compressor running at approximately 900 rpm. He successfully measured the instantaneous temperature inside the cylinder, which suggested a large gas suction heating.

Experiments of flow in inlet manifolds of IC engine were conducted by Bauer et al. (1998) with the purpose of analyzing heat exchange for different flow parameters. The instrumentation of the manifold was made with thermocouples, distributed in 5 positions along the manifold, and four heat flux sensors in each section. Next to the exit, the port was arranged to fit, alternatively, a hot-wire, a cold-wire and a heat flux sensor. The cold-wire probe calibration was made to allow temperature measurements up to 100°C, with a correction for thermal inertia using a fixed time constant of 2 ms, derived from energy balance and heat transfer correlations for the wire sensor. The authors concluded that the period in which the flow is stagnated contributes strongly to the total heat transfer to the fluid in the inlet manifold.

Zend and Assanis (2003) analyzed heat transfer in inlet manifolds of IC engines, pointing out that during the operation cycle, the air flow inside the manifold is composed of two phases, associated with periods in which the admission valve is either open or closed. The authors developed a new correlation to characterize the transient nature of the flow. In an experimental investigation of flow through inlet and discharge manifolds of diesel engines, Olczyk (2008) identified that the main difficulties in measurements of temperature transient are related to the sensor time response and the signal interpretation. The experiments adopted thermocouples, hot-wires and cold-wires in an apparatus capable of generating pulsating flows with frequencies up to 180 Hz. A methodology was proposed to take into account thermal inertia in the measurements carried out with the cold-wire sensor, which does not require any information about its constructive parameters.

Seeking to characterize the instantaneous superheating in reciprocating compressors operating at high speeds, Morriesen and Deschamps (2009) measured the instantaneous temperature inside the suction chamber of compressor operating at 3600 rpm. Using an anemometry system, one single probe was used to measure both velocity and temperature inside the compressor suction process. A sudden temperature decrease was found during the suction valve opening, followed by an increase in the gas temperature during the suction valve is closed.

From the review given, it is observed the potential of the single point measurement techniques such as cold-wires and micro-thermocouples to measure temperature transients in suction systems of IC engines as well as in refrigerating compressors. In the present paper, an experimental investigation of thermal transients is carried out in the suction chamber employing two different instruments in order to broaden the transient measurement technique in refrigerating compressors. The main concern here is to assess a complementary technique for analysis of the gas superheating through the use of instant temperature and velocity measurements together with pressure inside the suction chamber.

2. EXPERIMENTAL SETUP AND PROCEDURE

A reciprocating compressor operating with R134a was selected for the analysis, being submitted to two operating conditions, represented by two pairs of evaporation and condensation temperatures: (-23.3ºC/54.4ºC) and (-35.0ºC/54.4ºC). The first condition defines the pressure in the suction and discharge lines as 1.149bar and 14.71bar, respectively. When the evaporation temperature is lowered to -35.0ºC, the suction pressure becomes equal to 0.6617bar.

Piezoelectric pressure transducers were selected for the measurements in the suction chamber, due to their high response frequency, small size and reliability regarding the hostile conditions inside the compressor. To correlate the pressure measurement with the crank angle, a sensing winding was assembled to the crankcase to collect the signal emitted by a magnet fixed to the crankshaft. The instantaneous crankshaft position is calculated taking into account the compressor mechanism characteristics. Small sensing windings were also assembled into the valve plate seat to give the valve lift according to the crankshaft position.

Measurements of temperature were conducted in two ways: by a cold-wire and by a micro-thermocouple. The cold-wire used a DANTEC anemometer system composed by a constant current module (90C20). The micro-thermocouple used was an OMEGA® model CHAL-0005, chromel-alumel with wire diameter of 12.5 μm. Yet, for velocity measurements, a DANTEC mini-CTA system (54T30) was adopted. A single 5 μm diameter tungsten wire sensor (55P11) was employed for both velocity and temperature measurements. The sensor was calibrated for velocity measurements by using a DANTEC calibration unit (90H10), with a temperature sensor (55A76) being employed to register any significant variation during the process.

In the present work, the calibration procedure for temperature consisted in placing the cold-wire sensor inside a cavity next to a thermistor. Then, by adjusting the power of a heater inside the cavity to different levels, the signal of both the sensor and the thermistor were registered, allowing a calibration curve to be obtained for the cold-wire sensor.

For the hot-wire sensor, the calibration was carried with a DANTEC calibration unit (90H10), in which the sensor is exposed to a range of air flow velocities typically found in the suction chamber. Being the working fluid Tetrafluoroethane (R134a), the hot-wire calibration procedure had to consider the values of velocity and tension through dimensionless values, relating Reynolds with Nusselt according to Morriesen and Deschamps (2009).

An special probe were conceived aiming to attach the micro-thermocouple junction and make it easy to the mounted in the suction chamber, the design was inspired by the design of Lee and Smith (1980) though with some modifications. Essentially, the junction stays exposed to the flow and each one of its wires passes inside one of the two holes of a ceramic tube. To the muffler assembly an machined M6 screw was glue externally to the ceramic tube to provide an fix support for mounting. An simple sketch of the micro-thermocouple probe is shown in Figure 1.

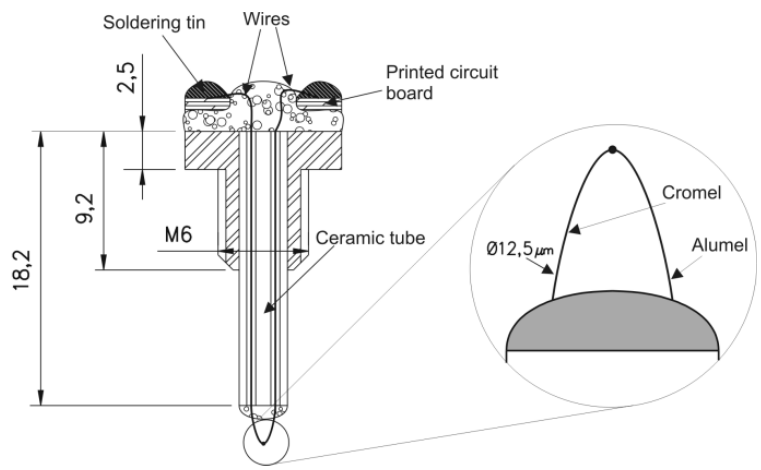

Figure 1. Micro-thermocouple probe design.

A calorimeter facility was employed to investigate the compressor under the specified operating conditions. The uncertainties associated with measurements taken with the calorimeter are ± 3% for mass flow rate and power consumption. Further details of the experimental facility can be found in Pereira *et al.* (2008). The compressor was tested three times for each operating condition. The acquisition system is composed of a computer, a National Instruments converter analogue/digital (A/D), model 6071E, and a program for data acquisition and reduction, developed using LabVIEW 8.6.

As illustrated in Figure 2a, the anemometry sensor was assembled at the entrance of the suction chamber, allowing measurements of velocity and temperature. A small tap hole (1 mm diameter) was used to connect the suction chamber to a larger orifice (7 mm diameter), in which the piezoelectric pressure transducer is mounted. An additional muffler was prepared in which the micro-thermocouple probe was mounted in the same position as the anemometry probe, though - due to the size of the micro-thermocouple probe - the sensor (thermocouple junction) became nearer the duct wall, see Figure 2b

The first step in the experimental procedure is to submit the compressor to an adequate vacuum condition, in order to remove air, humidity and any other contaminant inside the system. Then, the system receives a charge of refrigerant and the flowmeter reading is set to zero. After the compressor is switched on, a period of approximately 2 hours is needed to establish a fully periodic operating condition because of compressor thermal inertia. Finally, data for temperature, velocity and pressure in the suction chamber and displacement of suction valve are collected for 240 operation cycles of the compressor.

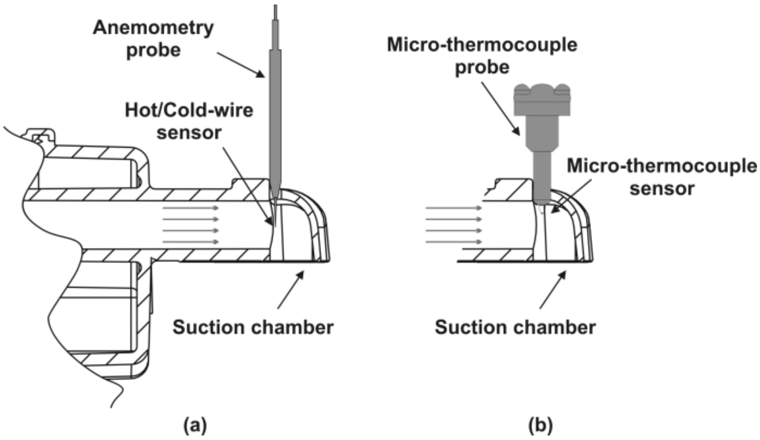

Figure 2. Detail of anemometry and micro-thermocouple probes assembly.

A total of 1000 measurements points were acquired per cycle to properly characterize the compressor operation cycle. Since the compressor operates at a velocity of 3600rpm, an acquisition rate of 60kHz was needed. The 240,000 experimental data collected along 240 cycles were submitted to a statistical analysis, with ensemble average results being expressed as function of the crankshaft angle. Data for energy consumption and mass flow rate were also acquired during compressor operation and they average values were evaluated.

Measurements of velocity at the entrance of the suction chamber were used to allow a correction in the experimental data for temperature, associated with the anemometer sensor thermal inertia. The corresponding temperature and pressure in the suction chamber were also measured to specify physical properties. Then, based on the Nusselt number, *Nu*, for each crankshaft position an estimate for the time constant τ_{wire} related to the anemometer sensor was obtained. The sensor inertia compensation was evaluated by Equation 1 deduced by Bruun (1995).

$$T_{corr} = T_{meas} + \tau_{wire} . \frac{\partial T_{meas}}{\partial t} \tag{1}$$

For the thermal inertia compensation of the micro-thermocouple three steps were taken, firstly and instant density was estimated using the pressure acquired during the anemometer measurement and the thermocouple uncorrected temperature, T_{meas}. Second, an instant flow velocity was evaluated using the mean flow rate of the compressor and the estimated instant density by Equation 2. At last, the instantaneous time constant τ_{TC} was calculated assuming the thermocouple junction as a sphere and its wires as two fins. Here also, Equation 1 was used to correct the sensor thermal inertia in this case the temperature measurements and time constant were from the micro-thermocouple.

$$U(t) = \frac{\dot{m}}{\rho(t) . A_{duct}} \tag{2}$$

3. RESULTS AND DISCUSSION

Figure 3 shows results for temperature variation along the compressor cycle for the operating condition of -23.3°C/54.4°C, with and without correction for thermal inertia of the cold-wire sensor. It can be noticed some noise in the temperature data when the correction is applied to the sensor measurement. In this study, a smoothing process was adopted to remove such a noise, in which a discrete Fourier transform is initially applied to the temperature data. With the signal in the frequency domain, high frequencies are removed and then, via an inverse transform, the smoothed signal is finally corrected for thermal inertia.

As can be seen, the correction adopted for thermal inertia allows one to recover part of the temperature transient information lost in the measurement. For instance, the sensor was originally able to follow the temperature variation of 4.2°C/ms occurring in the cycle between 240° and 263°. Considering thermal inertia, a response of 4.9°C/ms is seen for the corrected data between 230° and 251°. Furthermore, the maximum value for temperature in the cycle is increased from 54.2°C to 54.9°C, with a shift of 12° in the crankshaft position.

Adopting this correction technique to the signal from the micro-thermocouple, it is noted fast temperature transients can be assigned. For example, while the response of the micro-thermocouple was limited to 1.0 °C/ms between 253 and 268° angles, with the application of the correction response may be increased to 6.0 °C/ms between the angles 230 to 263°. Nonetheless, the adjusted signal has larger amplitudes of temperature, from 53.3 °C to 57.2 °C, with its occurrence point being lagged about 17° of the originally measured signal.

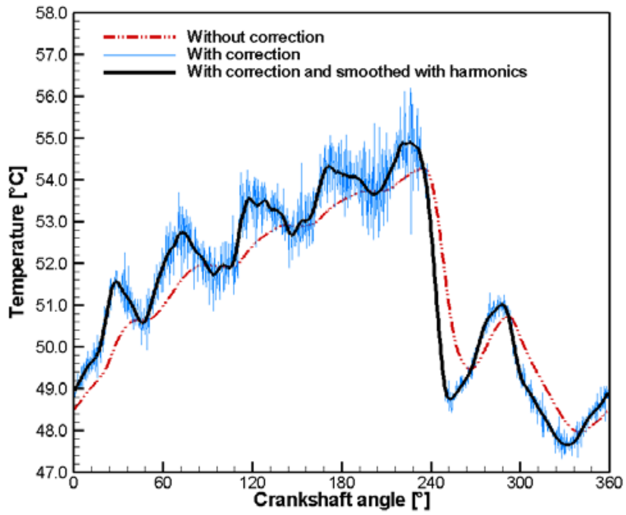

Figure 3: Correction in the temperature measurement of the cold-wire anemometer due to its thermal inertia.

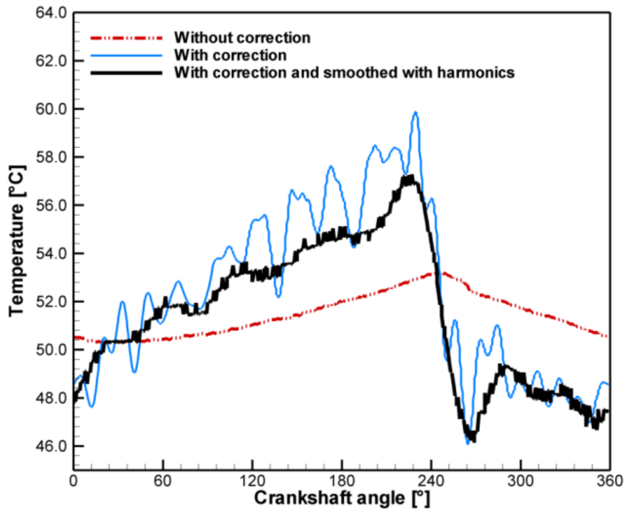

Figure 4: Correction in the temperature measurement of the micro-thermocouple due its thermal inertia.

In Figure 5, results for pressure, velocity and valve displacement are shown along the compressor cycle. It can be observed that the valve opening occurs at the angle of 230°, followed by a pressure drop and an increase in velocity, which reaches a maximum value of 32.2 m/s at the crankshaft angle of 264°. It is interesting to note that the points of maxima for velocity and valve displacement are not in the same crankshaft position. Since the hot-wire sensor was installed at the entrance of the suction chamber, the distance the fluid has to flow before reaching the suction port contributes for a delay between the data for velocity and valve displacement. The other aspect taking part in this situation is valve dynamics, since inertia does not allow the valve to instantaneously respond to steep variations of velocity and pressure.

Despite the difficulty originated by the two aforementioned aspects, it is clear that the velocity reaches its maximum value when the valve is fully open. It is also worthwhile noticing subtle variations in the velocity gradient around crankshaft positions 250° and 270°, probably due to perturbations in the flow. When the valve is closed, the sensor indicates the presence of velocity oscillations with amplitude of approximately 3 m/s. This phenomenon is associated with expansion and compression pressure waves traveling forward and backward in the duct that feeds the suction chamber. Naturally, the hot-wire sensor is insensitive to the velocity direction and, therefore, cannot detect an outflow condition in the suction chamber. Therefore, velocity magnitudes are always shown as positive.

Temperature variation in the suction chamber is due to heat transfer between the gas and the chamber walls, as well as pressure pulsation and interaction with the flow in the suction system. As can be seen in Figure 6 for the condition -23.3°C/54.4°C, pressure waves present during the suction process induce temperature oscillations. However, at the cycle positions 16, 28, 246 and 255°, within the period in which the valve is open, such variations are not perfectly in phase. The maximum and minimum temperature values in the suction chamber are equal to 54.8°C and 47.5 °C at the angles 227° and

331°, respectively. The temperature decrease observed when the valve opens can be attributed to the pressure drop to which the fluid in the suction chamber is submitted.

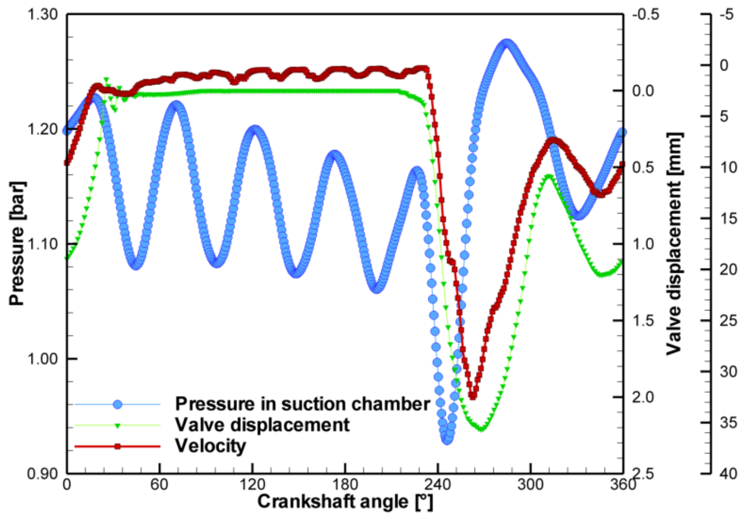

Figure 5: Measurements for temperature, pressure and velocity in the suction chamber.

For the period in which the valve is closed, between 26° and 230°, there is an increase of approximately 3.5°C in the suction chamber temperature. Considering that such a time period corresponds to 9.4 ms, this temperature increase indicates a high intensity heat transfer between the gas and the chamber walls.

Figure 7 shows a comparison between results for temperature in the suction chamber obtained at two operation conditions: -23.3°C/54.4°C and -35°C/54.4°C. As can be noticed, the average cycle temperature is increased from 51.4°C to 57.3°C when the condition is changed to -35°C/54.4°C. Moreover, the temperature reduction observed when the valve opens is almost 1°C greater for this condition. The other aspects already analyzed for the condition -23.3°C/54.4°C remains very similar in this new situation but, nevertheless, with a phase shift of 15° in the temperature and pressure oscillations.

It is interesting to observe the presence of two temperature oscillations during the period in which the valve is open for the condition -35°C/54.4°C. The first one occurs between the crankshaft positions of 280 and 330° and is linked to an increase of pressure in the suction chamber. On the other hand, the second oscillation can be attributed to heat transfer, since after the angle 330° the valve is almost closed and the fluid inside the chamber is virtually stagnated.

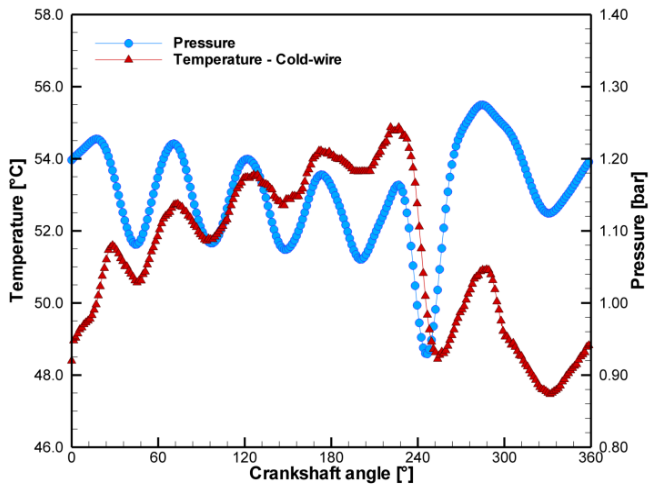

Figure 6: Pressure during the compressor operation cycle and temperature measured by the cold-wire sensor.

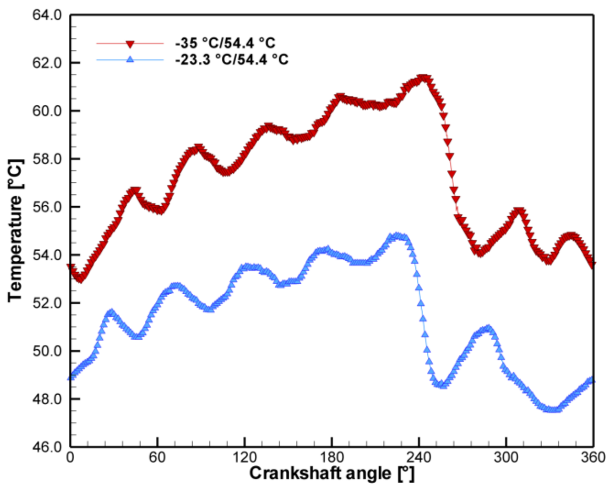

Figure 7: Cold-wire measurements for temperature along the compressor cycle for two operating conditions.

The instant temperature measurement with micro-thermocouple installed in the compressor operating at condition -23.3°C/54.4°C is comparable with the cold-wire probe measurement, as shown in Figure 8. However, the signal oscillations acquired by the micro-thermocouple are lagged with the oscillations recorded by the cold-wire probe along the cycle.

Additionally, it is verified a higher temperature increase indicated by the micro-thermocouple than the cold-wire sensor in the oscillatory flow interval, reaching values above 61.7°C at condition -35°C/54.4°C. Finally, it is also observed that the micro-thermocouple cannot register the fast variation of the flow temperature when the valve is open, referring to interval between 246 and 360°.

At condition -35°C/54.4°C the micro-thermocouple showed, approximately, a constant lagged in relation to the cold-wire sensor signal along the oscillatory flow as shown in Figure 9. Here again, the micro-thermocouple signal extrapolates the temperature variation amplitude though during the suction valve opening.

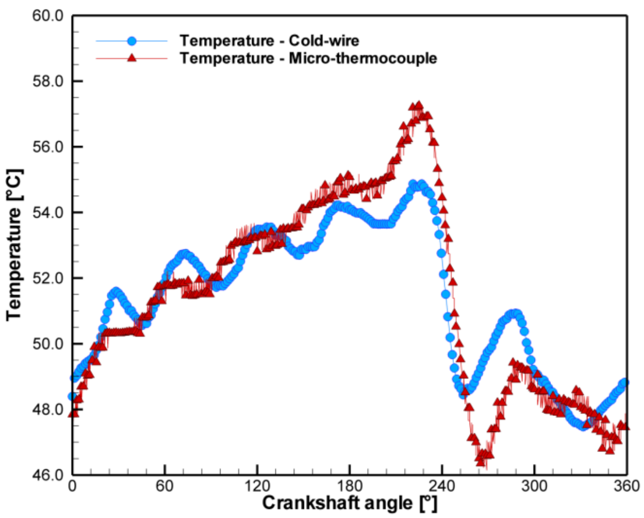

Figure 8: Pressure during the compressor operation cycle and temperature measured by the cold-wire sensor.

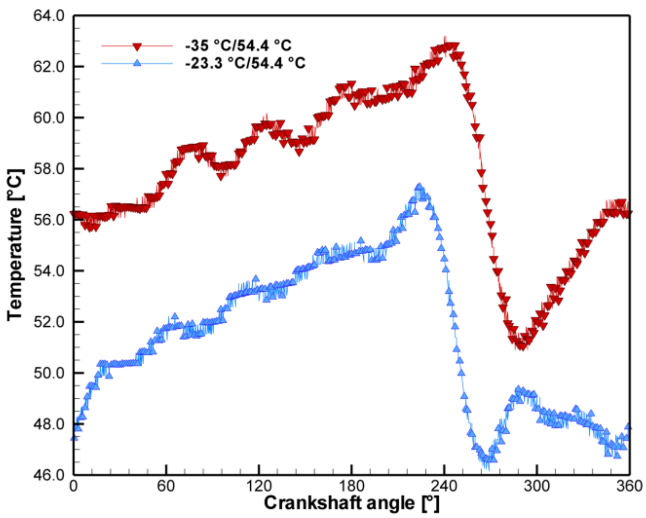

Figure 9: Temperature variation along the compressor cycle for two operating conditions, measured by the micro-thermocouple.

4. CONCLUSIONS

An experimental setup was developed to investigate thermal transients in the suction chamber of high speed refrigeration compressors. To this extent, a hot-wire system with a 5μm diameter wire probe was adopted for temperature and velocity measurements, also a micro-thermocouple probe specially designed for the experiments was used in temperature measurements. Moreover, corrections were made to temperature measurements at each position of the compressor operation cycle, estimating the thermal inertia of both sensors. Results for valve displacement and pressure pulsation in the suction chamber were also obtained to complement the analysis. Measurements indicated abrupt variations in all flow properties, strongly linked to the valve motion. When the valve is open, velocity reach levels of approximately 32 m/s, in comparison with 3 m/s when it is closed. It has been observed a considerable increase in the gas temperature during the period the suction valve is closed associated with heat transfer between the gas and the suction chamber walls. Although it does not have the same accuracy of the anemometry cold-wire, the micro-thermocouple probe allows a qualitative analysis of superheating during the cycle.

5. ACKNOWLEDGEMENTS

This study is part of a technical-scientific program between the Federal University of Santa Catarina and EMBRACO, partially funded by CNPq (Brazilian Research Council) through Grant No. 573581/2008-8 (National Institute of Science and Technology in Refrigeration and Thermophysics). Support from FINEP (Federal Agency of Research and Projects Financing) and CAPES (Coordination for the Improvement of High Level Personnel) are also acknowledged.

6. REFERENCES

Bauer, W. D., Wenisch, J., Heywood, J. B., 1998, “Averaged and Time-Resolved Heat Transfer of Steady and Pulsating Entry Flow in Intake Manifold of a Spark-Ignition Engine”, Int. J. Heat and Fluid Flow, v. 19, pp. 1-9.

Bruun. H. H., 1995, “Hot-Wire Anemometry: Principles and Signal Analysis”, Oxford University Press, USA, 536p.

Lee, K., Smith, J.L., 1980, “Time Resolved Mass Flow Measurement for a Reciprocating Compressor”, Proc. of the 1980 Purdue Compressor Tech. Conf. Purdue, West Lafayette, USA, p. 51-57.

Morriesen, A., Deschamps, C.J., 2009, “Measurement of Temperature Transients in the Suction System of a Reciprocating Compressor”, Proc. 7th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, Krakow, Poland, 8 p.

Olczyk, A., 2008, “Problems of Unsteady Temperature Measurements in a Pulsating Flow Gas”, Meas. Sci. and Technol, v. 19. pp. 1-11.

Pereira, E.L.L., Deschamps, C.J., Ribas Jr, F.A., 2008, “Performance Analysis of Reciprocating Compressors through Computational Fluid Dynamics”, Proc. IMechE, Part E: J. Process Mechanical Engineering, v. 222, p. 183-192.

Prasad, B. G. Shiva, 1992, “Fast Response Temperature Measurements in a Reciprocating Compressor”, Proc. of the 1992 Purdue Compressor Tech. Conf. Purdue, West Lafayette, USA, p. 1385-1395.

Zend, P.; Assanis, D., 2003, “Time-Resolved Heat Transfer in Engine Intake Manifold”, Proc. Int. Symposiun on Transient Convective Heat and Mass Transfer in Single and Two-Phase Flows, Cesme, Turkey, pp. 1-11.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.