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Testing and modelling of a variable speed scroll compressor

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ABSTRACT

Variable speed compressors offer continuous control, low noise level, reduced vibration, low-start current, rapid temperature control, by operating the compressor at higher speeds initially, and better COPs than the conventional on/off control. However, there exist some drawbacks concerning the inverter efficiency, the effect of the inverter on the induction motor and the effect of variable speed on the compressor isentropic and volumetric efficiencies. This study gives some experimental results as to inverter and compressor performances: it can be observed that the inverter efficiency varies between 95% and 98% for compressor electrical power varying between 1.5 and 6.5 kW ; and that compressor efficiencies are not enormously influenced by compressor supply frequency, but depend mainly on compressor pressure ratio, except the tests developed at 35 Hz and one test at 40 Hz, for which the difference is attributed to the compressor internal leakages due to a lack of lubrication at low speeds. At 75 Hz there was also observed a slight degradation that can be attributed to the electromechanical losses that increase with compressor speed. A maximal isentropic efficiency of 0.65 for a pressure ratio of the order of 2.2 is obtained. The volumetric efficiency decreases linearly from 0.98 for a pressure ratio of 1.5 to 0.83 for a pressure ratio of 5.6. In spite of the test conditions (condensing and evaporating pressures up to 40 and 20 bar, respectively), the compressor performance stays unchanged. The experimental results obtained at 50 Hz are used to identify six parameters of a semi-empirical model which is then used to simulate the different tests developed at different compressor speeds. The simulated results are in very good agreement with those measured with averages errors of −0.5 K; +3 g s^{-1} and −24 W for the exhaust temperature, the refrigerant flow rate and the compressor electrical power, respectively. The results show that motor losses induced by the inverter are negligible.

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1. Introduction

Inverter-driven scroll compressors are of great interest because they offer continuous control, low noise level, reduced vibrations, low-start current, quick temperature control, by operating the compressor at higher speeds initially, and better COPs than with a conventional on/off control [1–3]. In fact, if one imagines an ideal inverter with an efficiency of 100% one concludes that when the refrigeration system works at part load, the compressor speed is decreased to supply the adequate refrigerant flow rate (lower than the full load rate), giving as a result a higher evaporation temperature, a lower condensing temperature and thus a better COP. But in reality there are two unknowns that influence also the COP:

- one concerns the inverter: how is the inverter efficiency being varied and how does it modify the induction motor performance?,
- the other one concerns the scroll compressor: what are the compressor performances at variable speed?

The testing conditions, and more precisely the compressor speed, must also ensure a proper lubrication to achieve a good reliability throughout the lifetime of the compressor and to reduce the internal leakages. Higher rotational speeds (or pressure ratio) also mean higher refrigerant exhaust temperatures, which can chemically degrade oil and refrigerant and can cause thermally induced mechanical failure. To avoid that, some researchers propose using some special techniques like refrigerant injection [4–7].

Even if the variable speed capacity control is the most energy efficient [8], there persist some problems of component integration and also a lack of information about the inverter performance throughout its operation range.

According to Afjei and Jenni [9], by introducing an inverter, two sources of losses are introduced:

- Primary losses coming from the inverter itself: conduction losses, switching losses and base power consumption.

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Nomenclature

AU	heat transfer coefficient, W K^{-1}
C	coefficient or factor
$\dot{H}$	enthalpy flow, W
$\dot{M}$	mass flow rate, kg s^{-1}
N	rotational speed, s^{-1}
n	number of tests
$\dot{Q}$	heat flow, W
R_p	pressure ratio
V	volume, m^3
v	specific volume, m^3 kg^{-1}
w	specific work, J kg^{-1}
$\dot{W}$	power, W
Z	coefficient

Subscripts

amb	ambient
cal	calorimeter
cor	Coriolis
cp	compressor
el	electrical
ex	exhaust
inv	inverter
loss	loss
m	motor
meas	measured
nom	nominal
r	refrigerant
ref	reference
s	isentropic or swept
sd	slip
sim	simulated
su	supply
v	volumetric
w	water or wall

Greek symbols

α	power loss coefficient
ε	efficiency or coefficient
$\bar{\varepsilon}$	error
η	efficiency
ϑ	error function
σ	standard deviation

- Secondary losses coming from the induction motor: additional losses due to the distortions by the non-sinusoidal inverter output voltage.

According to their measurements, the secondary inverter losses become negligible for switching (or carrier) frequencies higher than 1 kHz. They obtained inverter efficiencies varying between 80% and 96%, where the maximum occurs at the higher speed and load.

In this study, an inverter and a scroll compressor are characterized experimentally. This last one is also modelled by using a semi-empirical model. Here a variable speed compressor is used to cover a broader domain of cooling power: this configuration allows using a small compressor, which can turn at higher speeds to reach the same capacity as a larger one.

2. Test bench description

The compressor is a hermetic scroll, which is here tested with refrigerant R134a and polyolester oil. Its theoretical swept volume flow rate at 50 Hz (nominal speed of 2900 rpm) is 9.44 m^3 h^{-1}. The fixed and the orbiting scrolls are located in the upper portion of the closed housing, above the induction motor. In this kind of compressor, the refrigerant circulates first through the electrical motor, to cool it; then it enters into the compression chamber. A small lubrication pump is mounted on the crankshaft in the bottom of the compressor shell, which circulates the oil to the bearings and scrolls through an orifice located inside the crankshaft.

This compressor is confronted to a cooling motor problem, due to the high evaporation temperature, and to another problem concerning the scroll lubrication: when the compressor turns slowly, the pumping effect decreases and the compressor is poorly lubricated. Under these conditions, the compressor internal leakage could also become more important.

The compressor is supplied with a pulse-width modulated (PWM) inverter, which is used to regulate the compressor supply frequency and thus its speed. The inverter output frequency can be varied between 0 and 440 Hz, with a maximal output power of 30 kW. The inverter is used in the mode V/F control for constant torque loads and at a carrier frequency of 15 kHz.

The compressor and the inverter are installed inside two separated calorimeters to determine their ambient losses as shown in Fig. 1. The calorimeters work at a constant air temperature by manually tuning the fan coil water flow rate, which is used to compensate the heating contributions of the lamps and the compressor. For the inverter, the calorimetric thermal balance is preferred to any measurement of output power, due to the electrical disturbances created by the inverter itself that exclude the use of conventional power transducers.

The total conductances of the compressor and inverter calorimeters are estimated by calibration to 5.26 and 1.5 W K^{-1}, respectively.

The following measurements are carried out: compressor speed, inverter power, compressor supply and exhaust pressures and temperatures, compressor surface temperature.

On the calorimeters, some temperatures and the water flow rates are also measured.

Table 1 gives the measuring ranges and uncertainties for pressures, flows and electrical power. Two sources of uncertainty are considered for the temperatures: one coming from the thermocouple tolerance (±0.5 K) and other one coming from the data acquisition system (±0.3 K). Thus, an overall absolute uncertainty of ±0.6 K (relative uncertainty is smaller) is obtained.

The refrigerant mass flow rate is determined from the evaporator steady-state thermal balance, with an uncertainty estimated, by comparison with a Coriolis flowmeter, to ±3%. This comparison was only developed for 19 of the 60 tests carried out.

The compressor power is measured with a power transducer, only for the tests where it is supplied directly from the network at 50 Hz. In the other cases the inverter supply power is measured.

As in this test bench the compressor works at variable speed, its frequency is measured directly in the inverter control system. According to the inverter manufacturer, this frequency is given with an accuracy of ±0.01%.

Inverter and compressor calorimeter load cells, used to measure water flow rates by weight, were calibrated to reduce their uncertainties. In the tested range, the compressor calorimeter load cell has an uncertainty of ±0.4% and the inverter calorimeter load cell ±0.1%. By using the uncertainty propagation method an uncertainty for the compressor and the inverter calorimeter water flow rates of ±2.5% and ±1.5% are obtained, respectively.

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