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Characterization and modeling of a scroll expander with air and ammonia as working fluid

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HIGHLIGHTS

- A scroll compressor is modified to work as a scroll expander.
- Complete characterization the scroll expander with air and ammonia as working fluids.
- The influence of the input variables on the scroll expander's performance is identified.
- A semi-empirical model is proposed to predict the expander's performance.

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ABSTRACT

This paper presents the experimental characterization and modeling of a scroll expander. The expander used here is a scroll compressor modified to work as an expander. It is characterized in two experimental setups using air and ammonia as working fluids. The paper studies how the main operating variables (supply pressure and temperature, pressure ratio, rotational speed and lubrication) influence the performance of the scroll expander. A semi-empirical model is proposed to determine the scroll expander performance. This model uses some semi-empirical parameters (such as built-in volume ratio, leakage area and mechanical losses), obtained through experimentation, to calculate the mechanical power, supply mass flow rate and exhaust temperature. Using this semi-empirical model, the deviations in the calculated mechanical power, exhaust temperature and supply mass flow rate are ±9%, ±4 K and ±5% Hz.

1. Introduction

In recent years, the worldwide energy model has been questioned because it is largely based on the use of fossil fuels. The limitations of this model from the economic and environmental perspectives are becoming more apparent with time. Therefore, interest in other energy sources such as solar energy or waste heat recovery at lower temperatures has been increasing. The literature [1] usually regards "low-temperature" heat sources to be those whose temperatures are in a range between 353 and 423 K; "medium-temperature" heat sources to be between 423 and 723 K, and "high-temperature" heat sources to be above 723 K.

From the energy demand point of view, one of the most important consumers of energy is the residential sector, which in Spain accounted for 17% of the total energy consumption [2] in 2011. This energy is supplied in the form of electricity, space heating and cooling, and domestic hot water. Therefore, the objective of new energy supply technologies should be to produce these energy services in an efficient and economic way and with the lowest environmental impact. One of these technologies could be the new absorption systems. Absorption refrigeration cycles using ammonia as refrigerant can be converted into combined power and refrigeration cycles using appropriate expanders [3]. The high pressure of ammonia vapor at the generator outlet can be expanded down to the absorber pressure to produce mechanical power through a suitable expansion device. There are several configurations for these types of cycle [4]. The main differences between them are the number of pressure levels (single, double and triple effect), the way the mechanical and cooling power is

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Nomenclature

C	velocity (m s^{-1})
c_p	constant pressure specific heat (kJ kg^{-1} K^{-1})
c_v	constant volume specific heat (kJ kg^{-1} K^{-1})
h	specific enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
N	rotational speed (Hz)
n	number of tests (−)
P	absolute pressure (kPa)
$\dot{Q}$	heat flow (W)
Rp	pressure ratio (−)
Rv	built-in volume ratio (−)
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (K)
t	time (s)
V	volume (m^3)
v	specific volume (m^3 kg^{-1})
$\dot{W}$	mechanical power (W)

Subscripts

atm	atmospheric
break	break sensor
ch	chamber
crit	critical
ex	exhaust
in	internal
iso	isentropic
leak	leak stream
loss	losses
lub	lubrication
meas	measured
net	net value
pred	predicted
sound	sound velocity
st	standard
su	supply
thr	theoretical
total	total

Greek symbols

γ	adiabatic expansion coefficient (−)
η	efficiency (−)
τ	torque (N m)
σ	amount of lubricant (drop s^{-1})

produced (simultaneously or in parallel), and their flexibility to produce mechanical power, cooling power or both. These cycles are of great interest because they can use low temperature energy sources, but so far they have not been studied in detail largely because of the lack of information on the performance of suitable expansion devices for ammonia in the low capacity range. The expander is a key component in the design and performance of these cycles [5]. The production of mechanical power and cooling is strongly related to the expander's behavior and cannot be accurately predicted with a mere simplified estimation of this behavior. It is also difficult to find expanders that are efficient in the low capacity range and which are made of materials compatible with ammonia (steel or aluminum). These expanders are expensive and difficult to find on the market.

Two types of expanders can be used in combined absorption power and cooling cycles: dynamic and volumetric. A previous study [5] concluded that dynamic expanders have low efficiency in low mechanical power ranges. The authors recommended the use of volumetric expanders because of their higher expansion ratio and higher efficiency in the lower capacity range. The main drawback of most volumetric expanders is the need for lubrication [6] although it has been demonstrated that oil free expanders are technically feasible [7].

Several authors have studied volumetric expanders for such related applications as Organic Rankine Cycles (ORC) using different working fluids such as R-245fa [8] or R-123 [9] or to theoretically explore the effect of reverse optimization without modifying the scroll geometry [10]. Also these studies concluded that volumetric expanders are good candidates for small capacity applications due to their small number of moving parts, high reliability and availability in the market.

Scroll expanders are among the volumetric expanders that could be used. However, few studies have been made about their use in absorption power and cooling cycles. Ingley et al. [11] characterized an open-drive scroll expander using an experimental setup with air as the working fluid. The experimental setup allowed the supply pressure and the expander rotational speed to be set as well. The volumetric efficiency of the expander was quite attractive; however, the isentropic efficiency was found to be lower than expected. Ingley proposed that further work should be carried out to study how lubrication affects expander performance and to characterize the expander using ammonia as the working fluid. Demirkaya et al. [12] characterized an absorption combined power and cooling cycle using an open-drive scroll expander. The overall efficiency of the scroll expander ranged from 30 to 50% with superheated ammonia vapor. This paper presents the experimental characterization and modeling of the expansion process of ammonia in an open-drive scroll expander. It is characterized in two experimental setups using air and ammonia as working fluid. A semi-empirical model has been developed in which some input parameters make it possible to calculate the expander's behavior. The model was calibrated and validated using a battery of tests with both air and ammonia. The main contributions of this paper are the proposal of an experimental methodology for the complete characterisation of small scale expanders and the experimental data for the specific case of ammonia as working fluid.

2. Experimental setups

The expander was an open-drive scroll compressor (Sanden, model TRSA05, similar to the one tested by the group of Prof. Goswami [11,12] or in Ref. [13]) used in automotive refrigeration systems, which was modified to work as an expander. It was selected because it is cheap, compatible with ammonia (aluminum and steel) and can easily be modified to work as an expander. According to the manufacturer, the volumetric displacement per revolution in compressor mode is 53.9 cm^3, and the maximum supply pressure and rotational speed are 3500 kPa and 166 Hz. The built-in volume ratio is 1.9, calculated by measuring the cross section area at the suction and exhaust chambers.

2.1. Air test bench

The main components of the experimental test bench are an Atlas Copco FS4 air compressor (equipped with a dehumidification system), a heating system (with a steam boiler coupled to a heat