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Reynolds-number-dependent efficiency characterization of a micro-scale centrifugal compressor using non-conventional working fluids

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ABSTRACT

The selection of working fluids other than air is a key issue in improving the efficiency of new thermodynamic cycles intended for low-to-moderate temperature small power plants. The aim of this paper is to study whether the low efficiency typical of small turbomachinery is still a problem when using alternative fluids. Based on a new design of power cycles named balanced hybrid Rankine-Brayton cycles, five different fluids were selected as potential working fluids: carbon dioxide, propane, isobutane, pentafluoroethane and sulfur hexafluoride. Dimensional analysis was used to compare the performances of a micro-scale centrifugal compressor working in homologous points where the efficiency variation depends only on the Reynolds-number (*Re*). The influence of *Re* on efficiency was calculated by means of four different methods for comparative purposes. Numerical simulations were also carried out in order to validate the methodological approach proposed. The results show the efficiency variations as a function of *Re* for increasing fluid densities. All the non-conventional fluids studied provide better performance in terms of efficiency than air. Particularly, isobutane and propane have been identified as potential working fluids candidates for the aforementioned innovative power cycle.

1. Introduction and background

Power plants down-scaling has become a major challenge to promote a wider use of thermal renewable energy employing low-to-moderate temperature sources [1]. This may rise the contribution of solar [2], geothermal [3], biomass and waste energy [4] sources in future scenarios with increasing electricity distributed generation [5] and micro-combined heat and power systems [6]. However, a low temperature of the thermal source prevents the primary heat from being efficiently converted to electrical power. In such a case an extra effort should be paid to improve the thermodynamic cycles, which is the driving force of the authors' research in the renewable small-scale power plants field [7,8]. The selection of the working fluid is considered a key aspect in improving the efficiency of innovative cycles [9,10]. An important question when studying these cycles is whether the use of fluids other than air or steam may affect the efficiency of the polytropic processes, especially in low power cases using small-scale turbomachinery. This is precisely why the present paper is devoted to analyze these effects on micro-turbomachinery performance when using a novel power cycle based on working fluids other than air.

Micro-scale centrifugal compressors (MSCCs) are miniature turbocompressors (impeller diameter less than 30 mm) working at ultra-high speeds (more than 200,000 min^{-1}) [11]. This noteworthy down-scaling implies that the Reynolds-number (*Re*) could fall below a critical threshold under which viscous friction on the boundary layer becomes dominant according to Dixon [12]. This results in a certain efficiency loss, which severely affects the overall power cycle efficiency in small-scale power plants [13]. Conversely, at high *Re*, the boundary layers on the blades are generally turbulent and very thin, so they have little impact on the global flow field and its efficiency.

Organic Rankine cycles (ORCs) are considered a promising technology to drive forward micro and small-scale power cycles based on renewable heat sources [14,15]. Besides, novel conceptions of Brayton cycles using air [16] or fluids in supercritical conditions such as carbon dioxide (CO_2) [17,18] are also interesting for low power applications due to their high compactness and modularity [19]. In addition to power cycle applications, micro-scale centrifugal compressors may also be used in cryogenic reverse Brayton air refrigerators [20] and domestic heat pumps using 1,1,1,2-tetrafluoroethane (R134a), looking for better efficiencies than those given by currently used volumetric compressors [21,22]. Moreover, MSCCs are also of great interest for the air feeding of low-powered polymer electrolyte membrane fuel cells [23].

Rovira et al. proposed a novel balanced hybrid Rankine-Brayton (B-HRB) power cycle [24,25] oriented to low-to-moderate solar power plants. As its name suggests, features of both Rankine and Brayton cycles are coupled, i.e. the cycle includes a pump for the condensates

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Nomenclature

a	speed of sound (m/s)
b_2	impeller tip width (m)
B_{ref}	Dietmann and Casey empirical coefficient (–)
c	absolute velocity (m/s), also chord (m)
c_f	friction coefficient (-)
c_p	specific heat capacity (kJ/kgK)
D	characteristic diameter (m)
h	specific enthalpy (kJ/kg)
L	characteristic length (m)
$\dot{m}_s$	mass flow (kg/s)
M_{c_1}	inlet absolute Mach number (#)
N	rotational sped (min^{-1})
p	pressure (bar)
R	gas constant (J/kg K)
Re	Reynolds-number (–)
T	temperature (K)
u	blade velocity (m/s)
w	relative velocity (m/s)

Acronyms

ATM	Automatic Topology Meshing
B-HRB	Balanced Hybrid Rankine-Brayton
CFD	Computational Fluid Dynamics
GCI	Grid Convergence Index
MSCC	Micro-Scale Centrifugal Compressor
ORC	Organic Rankine Cycle
SST	Shear Stress Transport

Greek letters

γ	specific heat ratio (–)
η	efficiency (–)
λ	Moody diagram friction coefficient (Pa)
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2 s)
ρ	fluid density (kg/m^3)
Φ	flow coefficient (–)

Subscripts

$0x$	total/stagnation conditions
1	impeller inlet
2	impeller outlet
3	diffuser outlet
crit	critical
dif	diffuser
imp	impeller
sat	saturation

and a split compression stage. These high-efficiency power cycles use non-conventional fluids such as carbon dioxide (CO_2), isobutane, propane, pentafluoroethane (R125) and sulfur hexafluoride (SF_6). Hence, in order to characterize the compression stage for these B-HRB cycles, this study is devoted to analyze the performance of a micro-scale centrifugal compressor using these alternative working fluids.

The novelty of this paper lies in the calculation of the efficiency variation that takes place when a small turbomachine such as a MSCC works with the potential fluids selected for the new design of B-HRB power cycles. Similar works devoted to analyze the MSCC behavior in the particular compression stage proposed in these innovative power cycles have not been found in the scientific literature to the authors' knowledge. Therefore, this study can be of great interest to estimate the internal efficiency variation of turbomachinery when a certain fluid is selected for the maximization of the overall power cycle efficiency of B-HRB cycles. The idea behind this is to find out to what extent the low efficiencies of small turbomachinery usually working with air could be generalized to other fluids with different Reynolds-numbers. The methodology developed in this paper is applied to a reference micro-scale centrifugal compressor which is expected to work under B-HRB conditions for the compression stage. Selected fluids for this analysis are the ones chosen for the B-HRB power cycles and, also, air for comparative purposes. The obtained results will be used in the experimentation phase to be accomplished in the near future.

The methodology is described in Section 2. Dimensional analysis is used to compare the performances of a compressor working with two different fluids on homologous points with dynamical similarity conditions. It is shown that if the head coefficient as well as both fluid and blade Mach numbers remain constant, the efficiency variation of the homologous points depends only on the Reynolds-number variation. Besides, four efficiency correction methods are outlined including their own Reynolds-number definition. The methodology ends with the description of the numerical model built to validate the approach proposed. Performance calculations have been conducted in Section 3 to obtain the efficiency variations for air and the non-conventional fluids selected as a function of Reynolds-number. The Reynolds-number was modified using different inlet pressures and thus different fluid entry densities. In addition, the rest of performance parameters variations are discussed. The paper ends with a synthesis of major conclusions in Section 4.

2. Methodology

The aim of this paper is to study whether the typical low efficiency of small turbomachinery is still a problem when using non-conventional fluids. Hence, Reynolds-number dependence on micro-scale centrifugal compressors performance is investigated. A consistent methodology has been conceived in order to asses quantitatively this dependence. A set of homologous working points is obtained where efficiency changes depends only on Reynolds-number (Section 2.1). Then efficiency correction methods are presented with their own Reynolds-number definition (Section 2.2). Finally, a numerical model is presented to validate the methodological approach used (Section 2.3).

2.1. Calculation of homologous points for different fluids through dimensional analysis

The selection of homologous points in turbomachinery allows the identification of an equivalent set of design points. The idea behind this approach is to obtain equivalent working conditions (rotational speed, pressure ratio and mass flow) of a micro-scale centrifugal compressor when using different working fluids. If the fluid flowing through a given turbomachine is replaced with a different fluid of different density, ρ or viscosity, μ, the performance of the machine will be affected; the performance changes may be easily predicted by using dimensional analysis. Furthermore, the use of dimensional analysis applied to turbomachines working with different fluids has the advantage of making straightforward the determination of the operating points where the efficiency is expected to be the same. Because of dynamical similarity, efficiency changes will depend only on Reynolds-number. Hence, the calculation of these points provides the new working conditions to characterize the efficiency increases or decreases on account solely of fluid properties.

The set of homologous points is obtained by means of dimensional