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Research Paper

A numerical comparison between ideal and dense gas flow structures in the supersonic regime for a cascade of wedge-shaped straight plates

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HIGHLIGHTS

- Flow passing through a cascade has numerically simulated.
- Simple straight blades with keen edges are considered.
- Ideal gas (air) and R245fa gas in a supersonic flow regime are compared.
- Oblique shock is created in dense gas while a bow shock is in ideal gas.

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ABSTRACT

A real dense gas such as R245fa is mostly used in organic-Rankine-cycle turbine expanders. The dense gas effects should be taken into account, especially in the transonic and supersonic flow regimes. Oblique shock and the interaction of shock and separation on the turbine blades are phenomena that have little deviation between a real gas and an ideal gas. This research numerically simulated the flow passing through a cascade of simple straight blades with keen edges considered for an ideal gas (air) and dense R245fa gas in a supersonic flow regime. The blade geometry was selected so that the deviations between the dense and ideal gas flows would be clearer than that with actual blades. The AUSM density-based method and NIST real gas model were used to model the ideal and dense gas, respectively. A second-order scheme was used for discretization, and the shear stress transport (SST) model was for the turbulence. The results show that an oblique shock is created on the leading edge when the inlet Mach number is 2.18 in dense gas. In ideal gas, a bow shock is created at the front of the leading edge. Moreover, for a wall pressure coefficient distribution, the separation point in dense gas is posterior than that in ideal gas.

1. Introduction

Low-grade waste heat recovery is one of the most interesting opportunities for producing power. The most attractive scheme for this purpose is the Organic Rankine Cycle (ORC). Most components of the ORC have been sufficiently investigated except the expanders. The characteristics of expanders such as the geometry and operating conditions should be carefully considered to obtain the best performance [1–4].

On the other hand, a supersonic ejector refrigeration system uses low-grade heat to produce cooling, and the ejectors play an important role. This system is very suitable for industrial and domestic waste heat recovery. The effects of dense refrigerant gas in the systems due to high velocity should be carefully considered [5,6]. Good thermodynamic efficiency is achievable in the ORC by selecting an optimal working fluid and thermodynamic optimization. Overall, the efficiency of the cycle is limited by the expander efficiency. Therefore, the most important equipment in the ORC is the expander [7–9].

Turbomachinery is designed and evaluated based on Computational Fluid Dynamics (CFD) simulations, which use the ideal gas law to model the fluid thermodynamic properties. This assumes that the deviation between a real gas and an ideal gas is very small. When turbomachinery operates in regions where this assumption does not hold, real gas effects should be considered. This deviation from an ideal gas particularly occurs in ORC expanders, where the Mach number in the expander nozzles goes up to 1 which makes the flow supercritical.

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Nomenclature

A	flow passage area (m^2)
c	blade chord length (m)
$\dot{m}$	mass flow rate (kg/s)
M	Mach number
M	molecular weight (g/mol)
P	pressure (Pa)
R	gas constant (J/kg-K)
t	blade thickness (m)
T	temperature (K)
u	Acentric factor
x	distance from the leading edge along the chord (m)
Z	compressibility
γ	heat capacity ratio
δ	angle between the wedge surface and flow axis
θ	angle between the oblique shock and flow axis
ρ	density (kg/m^3)

Subscript

c	critical
in	inlet
0	stagnation
1	before oblique shock

There are several studies on real-gas flows over different geometries, including cascades, airfoils, and screw expanders [10–12].

Colonna's work may be the leading work in this subject [13–17]. His work is about the effects of real gas in siloxane MDM, which is applied in ORCs. They evaluated the influence of different equations of state on the computed aerodynamic performance in a 2D nozzle blade operating with siloxane MDM [18]. Their results were very similar for when they used the Span-Wagner and Peng-Robinson-Stryjek-Vera equations. Hoffren et al. [19] computed the turbulent viscous real gas flows through of a radial ORC turbine stator using Toluene vapor. Zhang et al. [20] investigated the real gas effects of R123 in a nozzle flow using three-dimensional steady turbulent Navier-Stokes simulations. They showed that the derivations of the speed of sound and density at the nozzle inlet were about 15–20%. Furthermore, there was a deviation of about 10 m/s in the nozzle outlet velocity.

Lujan et al. [21] analyzed the real gas effects of R245fa in expansion processes. They evaluated two equations of state (ideal gas, Redlich-Kwong-Soave (RKS), and Penge Robinson (PR)). They concluded that the PR and RKS equations predict the flow with deviation less than 10%, while the deviation with a perfect gas assumption was more than 100%. Wheeler and Ong [22] studied real gas flows and discussed a novel method for designing nozzles that operate with dense gases. They showed that in ORC expanders, the inviscid gas dynamics and preliminary vane or blade designs can be determined using the polytropic index *k*. Schnerr and Leidner [23] described the influence of dense gas effects of a normal shock near a curvature. In a real gas flow, the logarithmic singularity at the shock foot point remains in the disturbance velocity and causes post shock expansion behind a compression shock if the wall is convex.

Congedo et al. [24] numerically studied dense gas flows in an ORC turbine. Their analysis was done using both the Span and Wagner and Peng–Robinson–Stryjeck–Vera equations of state for a wide range of operating conditions to check if the contrast was only weakly dependent on the thermodynamic model.

Harinck et al. [25] presented a comparison of the effects of using different thermodynamic models for the CFD of turbo-expanders. They applied the polytropic ideal-gas law, the Peng–Robinson–Stryjek–Vera equation of state, and the highly accurate multi-parameter equations of state. They also considered steam, toluene, and R245fa. They concluded that compared to low-complexity fluids like water, for complex fluids like toluene and R245fa, the deviations in density, speed of sound, and velocity obtained from the use of the polytropic ideal-gas model vary strongly along the isentropic expansions.

There are a few studies about the effect of real R245fa gas as the mostly used working fluid in the ORC. Previous works studied the effects of real gas using equations of state in their CFD modeling of energy conversion machines (turbines or expanders) in ORCs. All previous works investigated the best thermodynamic models or general efficiency of energy conversion machines. In this study, a special cascade of straight wedge-shaped plates was selected to investigate different phenomena, such as oblique/bow chokes and boundary layer separation. The focus in this study is the effects of dense gas using R245fa.

2. Fluid thermodynamic model

Also known as 1, 1, 1, 3, 3-pentafluoropropane, R245fa is a common refrigerant used in ORC systems. It is characterized by a positive slope of the saturated vapor line in the T-s diagram, which prevents the formation of liquid droplets at the exit of the expander [26]. The properties of R245fa are shown in Table 1. Using databases such as NIST REFPROP [27] or CoolProp [28] is the most accurate way of modeling a fluid [29]. In NIST REFPROP, fluid properties are defined with multi-parameter equations of state based on Helmholtz free energy [27].

The estimated uncertainty in the equation of state for density is 0.1% in the liquid phase below 400 K with pressures up to 30 MPa. Above 30 MPa, the uncertainties are 0.2% at temperatures above 310 K and up to 1% for lower temperatures. In the vapor phase and at temperatures above 400 K, the uncertainty is 1% in density, with higher uncertainties in the critical region. The uncertainty in vapor pressure is 0.2% above 250 K, and it rises to 0.35% above 370 K. The uncertainties in other properties are 5% in the liquid phase heat capacities and 0.2% in the liquid phase sound speeds below 360 K, with unknown uncertainties outside of these regions due to a lack of experimental data [30].

The simplest thermodynamic model (a relation between pressure, volume, and density) involves an ideal gas assumption. In an ideal gas, interactions are perfectly elastic. The ideal gas model tends to fail at lower temperature and higher pressure, where intermolecular forces and molecular size become more important [31]. Expansion in the ORC inlet pressure occurs in the vicinity of the critical pressure, and the temperature is high enough to underestimate the molecular volume. Thus, a supercritical ORC or high evaporator temperature should not be studied with ideal gas laws. A compressibility factor defined as $Z = p/(\rho RT)$ [32,33] is usually used to quantify the deviation of a real gas from an ideal one. In this study, the compressibility factor Z was 0.8.

Table 1
Properties of R245fa [27].

Value	Symbol	Value
Critical temperature	T_c	427.16 K
Critical pressure	P_c	3.651 MPa
Critical density	ρ_c	516.08 m^3/kg
Acentric factor	u	0.3776
Molecular weight	M	134.05 g/mol