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Flow and heat transfer characteristics of r22 and ethanol at supercritical pressures

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ABSTRACT

This paper presents an experimental investigation of the flow and convection heat transfer characteristics of R22 and ethanol at supercritical pressures in a vertical small tube with an inner diameter of 1.004 mm. The heat flux ranges from 1.1×10^5 W m^{-2} to 1.8×10^6 W m^{-2}, the fluid inlet Reynolds number ranges from 3.5×10^3 to 2.4×10^4, and the pressure ranges from 5.5 MPa to 10 MPa. The results show that for supercritical R22, the frictional pressure drop increases significantly with the heat flux. At p = 5.5 MPa, Re_{in} = 12,000 and a heat flux of 10^6 W m^{-2}, the local heat transfer is greatly reduced due to the low density fluid near the high temperature wall. Both buoyancy and flow acceleration have little effect on the heat transfer. For supercritical ethanol, the frictional pressure drop variation with the heat flux is insignificant, while the local heat transfer coefficient increases as the enthalpy increases. Ethanol gives better flow and heat transfer performance than R22 at supercritical pressures from 7.3 MPa to 10 MPa for heat fluxes of 1.1×10^5–1.8×10^6 W m^{-2}.

1. Introduction

The third fluid cooling technology is developed to protect the high heat flux surface in combustion chamber in liquid rocket engines. In the third fluid cooling system, the third fluid besides the oxidizer and the fuel, which are referred as propellant, is introduced as the coolant and circulated to cool the nozzle and combustor assembly. The third fluid is contained in a closed-loop cycle with the high temperature combustor wall as the heat source and the low temperature fuel as the cold sink [1]. The coolant is circulated by a turbine-driven coolant pump through the passage formed by a jacket enclosing the nozzle and combustor assembly with high heat flux from the combustor absorbed by the coolant, and then fed into the turbine to produce work by expansion for driving the oxidizer pump, coolant pump and fuel pump. Afterwards the coolant vapor condenses in a heat exchanger to heat the fuel or oxidizer or both; thereby returning the heat from the combustor to the propellant fed into the combustion chamber. In the third fluid cooled liquid rocket engine, since the coolant is circulated outside the chamber, the turbine outlet pressure is reduced and much higher turbine expansion ratios can be obtained. Moreover, all of the propellant is fed to the combustor which can operate at higher pressures; thus, the output thrust is increased.

During the heat absorbing process in the jacket enclosing the nozzle and combustor assembly, the coolant (the third fluid) is usually above its critical pressure, while during the heat rejection process the coolant (the third fluid) heats the propellant at sub-critical pressures and condenses. R22 and ethanol have been suggested as working fluids for third fluid cooling cycles in view of their thermophysical properties, heat transfer and flow resistance properties, critical parameters and safety. When the fluids are at supercritical pressures such as when absorbing heat from the nozzle and combustor assembly, small fluid temperature and pressure variations can result in drastic changes in the thermophysical properties as shown in Fig. 1 [2]. The specific heat, c_p, reaches a peak at a certain temperature defined as the pseudo critical temperature, T_{pc}. Other properties including the density, thermal conductivity and viscosity also vary significantly within a small temperature range near T_{pc}. The flow resistance and heat transfer are then expected to exhibit many special features due to the significant property variations and the consequent buoyancy and flow acceleration effects [3].

In addition to the third fluid cooling systems, flow and convection heat transfer of supercritical fluids also occur in many other industrial applications including aerospace engineering, power engineering, chemical engineering, enhanced geothermal systems, CO_2 storage and cryogenic and refrigeration engineering. For

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Nomenclature

Bo*	non-dimensional buoyancy parameter
c_p	specific heat at constant pressure [kJ kg^{-1} K^{-1}]
d	tube diameter [m]
g	gravitational acceleration [m s^{-2}]
G	mass flux [kg m^{-2} s^{-1}]
Gr*	Grashof number
h_x	local heat transfer coefficient [W m^{-2} K^{-1}]
k	turbulence kinetic energy [m^2 s^{-2}]
I	heating current [A]
i	bulk specific enthalpy [J kg^{-1}]
Kv	non-dimensional flow acceleration parameter
p	pressure [MPa]
Pr	Prandtl number
Q	heat quantity [W]
q	heat flux [W m^{-2}]
R	inner radius of small tube [m]
r	distance from the axis [m]
Re	Reynolds number
T	temperature [°C]
u	velocity [m s^{-1}]
x	axial coordinate [m]

Greek symbols

α_p	thermal expansion coefficient [K^{-1}]
β_T	isothermal compression coefficient [Pa^{-1}]
δ	tube wall thickness [m]
λ	thermal conductivity [W m^{-1} K^{-1}]
μ	molecular viscosity [Pa s]
ρ	fluid density [kg m^{-3}] or electrical resistivity [Ω m]

Subscripts

ad	adiabatic section
f	fluid
i	inner surface
in	inlet
o	outer surface
out	outlet
pc	pseudo critical
p	induced by pressure variation
T	induced by temperature variation
w	wall

instance, platelet transpiration cooling uses hydrogen or methane at supercritical pressures flowing through chemically etched coolant micron scale channels in the platelet formed by bonding together thin metal sheets to protect high heat flux surfaces such as rocket thruster walls [4]. In power engineering applications, supercritical pressure water is widely used as the working fluid in thermal power stations. In the supercritical pressure water-cooled reactor (SPWR), the supercritical pressure water absorbs fission heat from the fuel assembly in the reactor core and enters the turbine at high temperature and high pressure, which enhances the thermal power cycle efficiency. Supercritical pressure water is also being actively considered as the coolant for the breeder blanket in fusion power plants [5].

Comprehensive researches on the in-tube flow and convection heat transfer of supercritical fluids have been conducted in the past several decades by Petukhov [3], Domin [6], Protopopov [7], Polyakov [8], Shitsman [9], Bourke et al. [10], Hall [11], Jackson and Hall [12,13], Bringer and Smith [14], Schnurr [15], Tanaka et al. [16], Shiralkar and Griffith [17] for applications of supercritical fluids in various industrial fields. The working fluids have mostly been

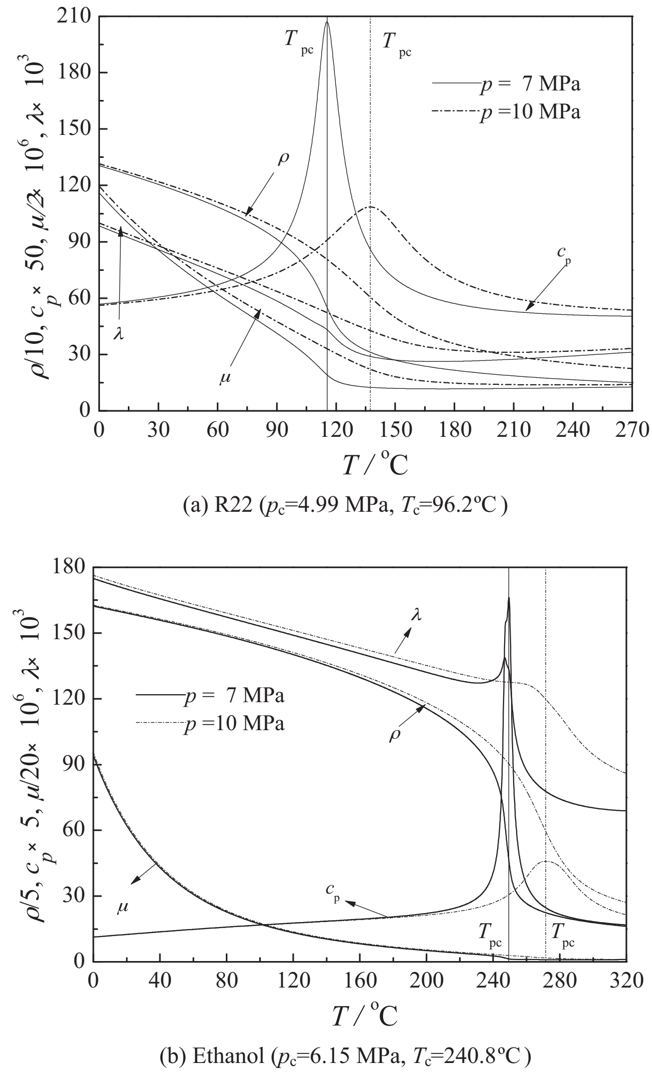

Fig. 1. Thermophysical property variations with temperature.

water and carbon dioxide. These results have provided significant insight into the special features of the in-tube flow and convection heat transfer of supercritical fluids. Several correlations have been developed for the pressure drop and heat transfer coefficient of supercritical pressure fluids during heating based on the experimental and theoretical results.

Tarasova and Leont'ev [18] measured the flow resistance of supercritical water flowing through 3.34 mm and 8.03 mm smooth vertical tubes during heating and found that the measured results were lower than the values of those without heating near the critical point due to the viscosity decrease. Razumovskiy [19] claimed that the pressure drop resulting from the density variation could not be ignored for large ratios of the heat flux to the mass flux based on their studies of supercritical water flowing through a 6.28 mm smooth vertical tube during heating.

For the heat transfer, Shitsman [9] found that, for relatively large tubes (d_{in} = 8 mm for example), the local wall temperatures varied non-linearly and local heat transfer deterioration was observed in buoyancy-aided flow cases (upward flow in a heated passage) resulting from the buoyancy effect whereas in buoyancy-opposed flow cases (downward flow in a heated passage) the local wall temperature varied smoothly. Jackson and Hall [12] explained the in-tube buoyancy affected convection heat transfer behavior for supercritical fluids using a semi-empirical theory and proposed a