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The status of the research on the heat transfer deterioration in supercritical fluids: A review

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ABSTRACT

Nowadays, both experimental and computational research on the turbulent convective heat transfer to supercritical fluids is particularly active, especially because the actual poor comprehension and prediction of the possible heat transfer deterioration is limiting the design of new promising engineering applications. In this review, such applications, among which supercritical water-cooled nuclear reactors, supercritical CO_2 power generation cycles, and oxygen/methane-fuel rocket engines, are firstly introduced. Then, after a phenomenological description of the heat transfer deterioration, the status of the research is analysed in details, highlighting the major advantages and limitations of both experimental and computational studies performed so far. The review demonstrates that experimental research is mostly focused on finding simple heat transfer correlations rather than detailed models. Also detailed numerical insight of the problem is still almost unexplored. The main conclusion is that new approaches, possibly integrating extensive experiments and computations, are needed to shed new light on the problem of heat transfer to supercritical fluids.

1. Introduction

The desire to increase the performances of many engineering systems based on thermodynamic cycles has opened the field to high pressure fluid systems. In fact, an increase of the fluid pressure generally results in a higher efficiency of the thermodynamic cycles as well as a greater compactness of the systems. However, the behaviour of the fluids when pressure increases can be substantially different from the behaviour at ambient pressure. The major change occurs when the fluid exceeds the thermodynamic critical pressure, mainly because the vapour-liquid phase change does not occur anymore. Engineering systems that uses supercritical-pressure fluids (shortly said as supercritical fluids) take advantage of the single-phase behaviour of the flow and compact design, even if it is paid in terms of higher mechanical stress to the solid structures. Presently, supercritical fluids are extensively used in many industrial applications, processes and systems such as power generation, cooling, fluid extraction, hydrolysis, gasification, and drying. Moreover, supercritical fluids are planned to be used in many new promising applications, including innovative air-conditioning and refrigeration systems, nuclear power plants, power conversion systems, waste management, and rocket engines fed with innovative propellants. Many of these envisioned applications consider some kind of turbulent convective heat transfer to supercritical fluids. This type of heat transfer is substantially different from the heat transfer to low-pressure fluids. For instance, although the risk of boiling crisis, typical of subcritical-pressure-fluid flows with high heat flux, is prevented because two-phase flow does not occur, a risk of hazardously high wall temperatures still exists when pressure is supercritical. The nature of this phenomenon, generally referred to as heat transfer deterioration and first experimented in Ref. [1] for supercritical oxygen, is still not fully comprehended and, even more important in sight of new engineering applications, it is hardly predictable. Nowadays, the necessity to accurately predict the heat transfer in new technological devices that use supercritical fluids pushes the research to find an accurate heat transfer description. This necessity becomes even more urgent in applications like nuclear power plants or rocket engines using supercritical fluids because a wrong estimation of the wall material temperature could result in a catastrophic failure.

The present review describes the scenario of the research on this topic, firstly describing the engineering applications where the heat transfer to supercritical fluids is crucial, secondly the phenomenon of heat transfer deterioration, and finally the status of both experimental and computational activities.

2. The technological impact

Currently, the most relevant industrial application involving heat transfer to supercritical fluids is the fossil-fuel power plant. In such system, supercritical water is utilised to enhance the efficiency of the steam generator because the problem caused by the occurrence of the

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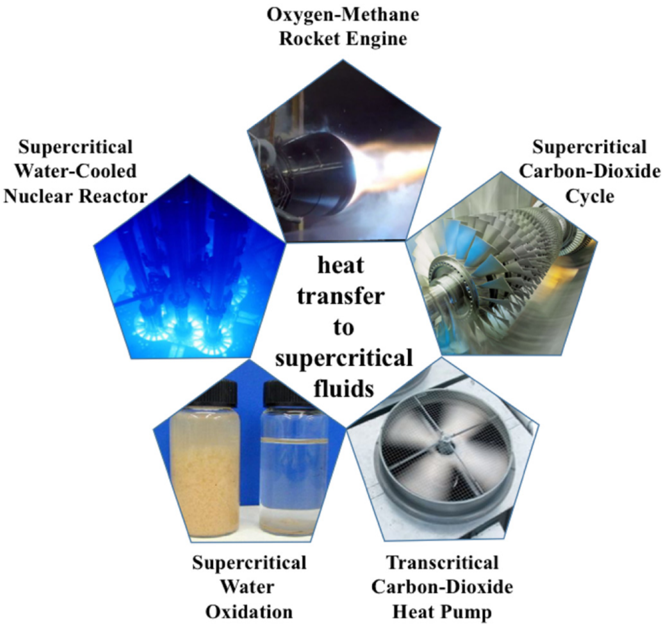

Fig. 1. The technological impact of the heat transfer to supercritical fluids.

critical heat flux due to the liquid-vapour phase transition occurring at subcritical pressures is avoided and thus a larger turbine inlet temperature can be reached. The thermal efficiency of the recent fossil-fuel power plants using supercritical-water has achieved about 45% for the fluid at 500 °C and 300 bar. Although in such power plants deterioration in heat transfer may occur, it generally occurs only within a narrow range of operative parameters and thus does not jeopardise the safety of the system [2].

The most relevant engineering applications of future realisation whose development may be limited by the poor comprehension and prediction of the phenomena related to the heat transfer to supercritical fluids are sketched in Fig. 1 and briefly discussed in what follows.

2.1. Supercritical Water-Cooled Nuclear Reactor

One of the most promising type of nuclear reactors that will be available after 2030 is the Supercritical Water-Cooled Reactors (SCWR). It is basically a Light Water Reactor (LWR) operating at higher pressure (about 250 bar, whereas the water critical pressure is about 220 bar) and temperatures (up to 500 °C). The concept design of a SCWR enables significant simplifications of the system, thanks to the elimination of the steam generators, steam separators, and steam dryers, typical of the LWR [2]. Moreover, because of the increased inlet turbine temperature, it is expected that a SCWR will achieve efficiencies of about 44%, compared with current LWR efficiencies of about 34%. However, as supercritical water is used as neutron moderator and coolant, the occurrence of heat transfer deterioration could results in a catastrophic failure [3].

2.2. Oxygen-Methane Rocket Engine

Rocket engines are one of the first applications in which supercritical fluids have been used. In fact, the pressure in the combustion chamber is typically higher than the critical pressure of most of the adopted propellants, such as hydrogen, oxygen, and kerosene. Also methane, a new promising fuel to be used in conjunction with oxygen, will operate at supercritical pressure [4]. Methane-fed rocket engines are currently under study and development in USA (NASA, SpaceX, and Blue Origin), Europe (ESA, ASI, and CNES) and Japan (JAXA). The advantages of methane over conventional propellants are: tank-storability in liquid phase for long duration flights in order to replace toxic and hazardous propellants such as hydrazine and nitrogen tetroxide; more compact tank design than using liquid hydrogen; less carbon deposition with respect to kerosene that permits an efficient reusability of such rocket engines; and availability in the solar system (e.g., in-situ production on Mars and harvesting of the hydrocarbons seas on Titan). Anyway, to cool the combustion chamber wall, methane is pumped in suitable cooling channels that surround the combustion chamber. Preliminary estimations have shown that methane heat transfer deterioration may occur in such system [5].

2.3. Supercritical Carbon Dioxide cycle

The Supercritical Carbon Dioxide (S-CO_2) cycle is a power generation system which combines the advantages of both steam Rankine cycle and gas turbine cycle. In fact, supercritical carbon dioxide is compressed in the incompressible region (i.e., at subcritical temperature), which is an advantage of the steam Rankine cycle, while the turbine operates with a gaseous single phase fluid, which is an advantage of the gas turbine cycle. Accordingly, thermal efficiency can increase by 5% with relatively contained turbine inlet temperature range (450–600 °C) compared with other power conversion systems. However, in the heater element of the S-CO_2 cycle, a large heat transfer to the supercritical carbon dioxide is conceived [6].

2.4. Transcritical Carbon-Dioxide Heat Pump

Although not new as a refrigerant, carbon dioxide has gained renewed interest in recent years. In fact, being a nontoxic and inexpensive natural gas that has a zero net impact on global warming, it is considered as a good alternative to conventional refrigerants (generally fluorine- and/or chlorine based). The most relevant use of carbon dioxide as a refrigerant is found in the heat pump cycles of new generation [7]; in these systems, generally referred to as Transcritical Carbon-Dioxide Heat Pump, heat transfer to supercritical carbon dioxide occurs in the so-called “gas cooler” (corresponding to the condenser in the conventional subcritical cycle) when the heat pump is operated in cooling mode cycle.

2.5. Super Critical Water Oxidation

As the solubility properties of water dramatically increase at supercritical pressure, a recent idea is to destroy toxic aqueous waste using water at supercritical pressure. This method is called Super Critical Water Oxidation (SCWO). Destruction efficiencies of 99.9% or higher have been reported for a variety of toxic and nontoxic materials treated by SCWO. Because efficient oxidation reactions occur at temperatures in the range of about 400–650 °C, a large heat transfer to supercritical water is expected [8].

3. The physical problem

Turbulent convective heat transfer to supercritical fluids is strongly affected by the significant variation of thermo-physical properties in the region near the critical point. In fact, in the near-critical region, for a given supercritical pressure, properties such as density, speed of sound, viscosity, and thermal conductivity undergo a significant drop within a very narrow temperature range, while properties such as enthalpy and entropy undergo a sharp increase. Moreover, thermal expansion, and specific heats have a peak near the so-called “pseudo-critical” temperature T_{pc}, which is defined as the temperature at which specific heat at constant pressure has a maximum at a specified pressure. The magnitude of these peaks and drops decreases as pressure increases, and thus the influence of the near-critical region on the heat transfer diminishes for increasing pressure. As an example of the properties behaviour in the near-critical region, Fig. 2 shows density ρ, specific heat