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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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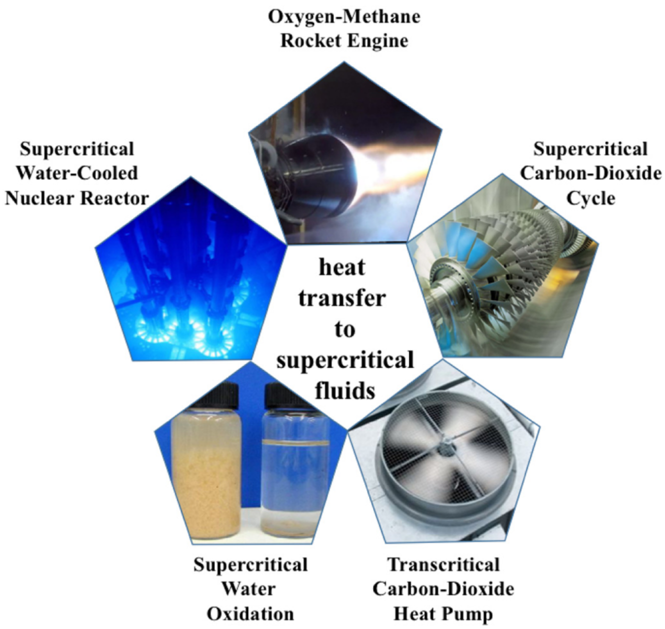

Fig. 1. The technological impact of the heat transfer to supercritical fluids.

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

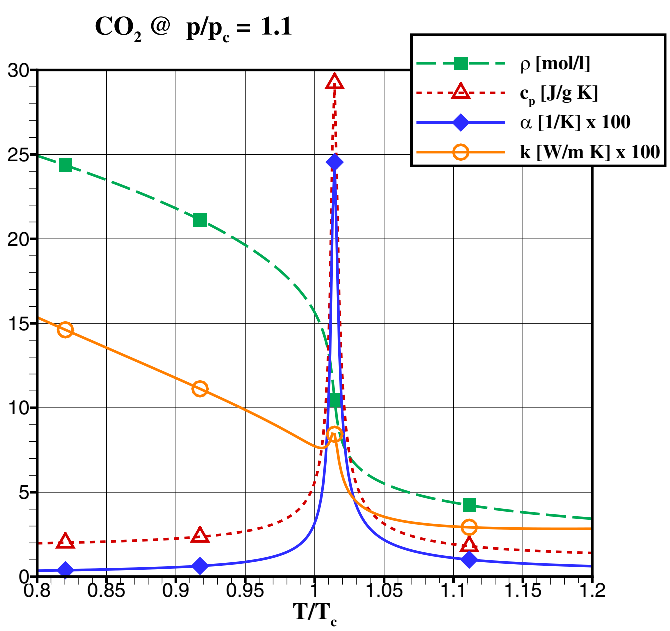

Fig. 2. Carbon dioxide density (ρ), specific heat at constant pressure (c_p), thermal expansion (α), and thermal conductivity (k) at p/p_c = 1.1.

at constant pressure c_p, thermal expansion α, and thermal conductivity k of carbon dioxide at the reduced pressure p/p_c = 1.1 and reduced temperature T/T_c between 0.8 and 1.2, where p_c and T_c are the critical pressure and temperature, respectively. This figure is obtained using the commercial software REFPROP [9].

In the near-critical region, the effectiveness of turbulent convective heat transfer is significantly influenced by the ratio of entering heat flux to mass flux, q_w/G. At relatively high mass flux or low heat flux, the heat transfer may be enhanced. Clear marks of heat-transfer enhancement are higher values of heat-transfer coefficient and lower values of wall temperature compared to those at "normal" heat-transfer mode. Normal heat transfer is commonly addressed to cases with heat transfer coefficient similar to the one at subcritical-pressure. The sharp increase of specific heat under near critical conditions (Fig. 2) is thought to be the main reason for heat-transfer enhancement. On the contrary, at relatively high heat flux or low mass flux a heat-transfer deterioration may occur, which is generally recognised by a substantial increase of wall temperature and a corresponding decrease of the heat-transfer coefficient. The evidence of the heat transfer deterioration can be appreciated in Fig. 3, where the experimental data of Shitsman (reported in the review paper [10]) are presented. Here it is possible to note that, for a given supercritical water upward flow in heated vertical tube, increasing the entering heat flux results in large and localised spikes of the wall temperature. In these experiments, the flow velocity was relatively small such that the effect of gravity induced buoyancy was decisive to induce heat transfer deterioration. In fact, in cases of relatively low velocity, experimental results for upward and downward flows are found to differ. For example, in Fig. 4 the experimental data of Jackson and Evans-Lutterodt (reported in the review paper [10]) on supercritical carbon dioxide in a vertical tube show that heat transfer deterioration is present only in upward flows. Experiments have also shown that when the flow is sufficiently fast, such that gravity induced buoyancy is not relevant, heat transfer deterioration can still occurs, of course regardless of the flow orientation [11]. The study of heat transfer deterioration is also complicated by the fact that there is still no unique identification for its onset. In fact, the heat transfer coefficient reduction and wall temperature increase take place rather smoothly (Figs. 3 and 4), compared to the sharp wall temperature increase that can be found when boiling crisis occurs at subcritical pressure.

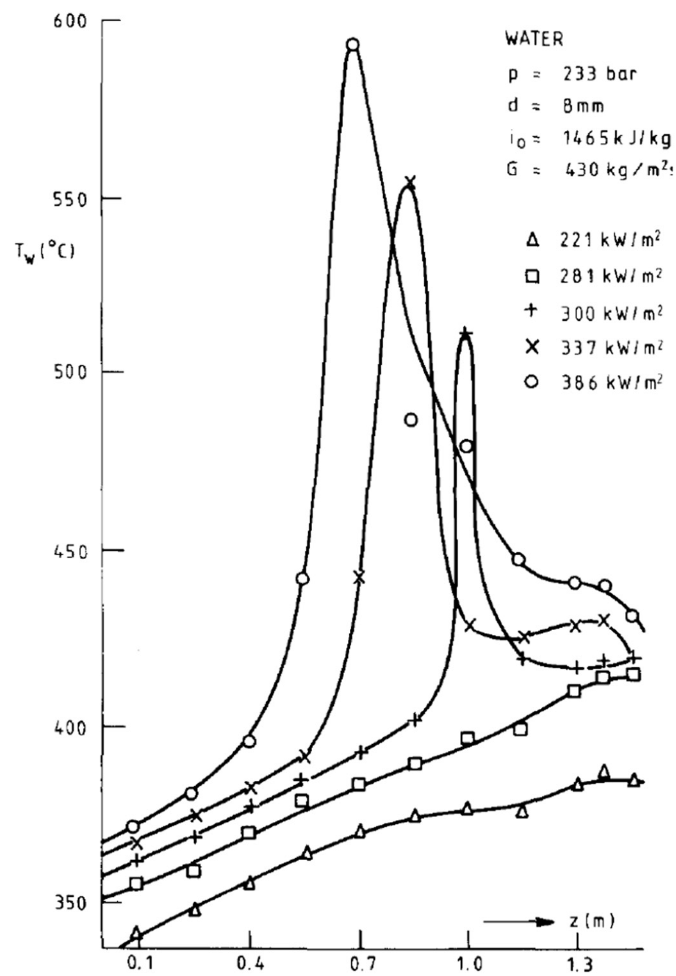

Fig. 3. Wall temperature measurements (y-axis) along a heated tube (x-axis) at increasing heat flux (figure taken from Ref. [10]).

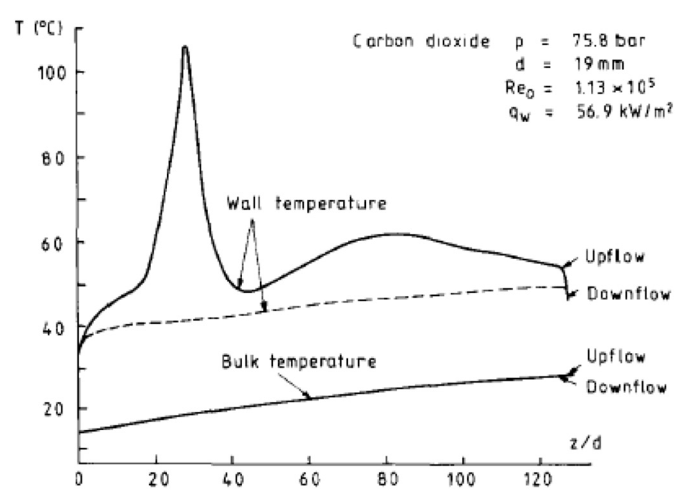

Fig. 4. Wall and bulk temperature measurements (y-axis) along a heated tube (x-axis) in vertical tubes with downward and upward flows (figure taken from Ref. [10]).

However, heat-transfer deterioration is recognised to be a consequence of turbulence production being reduced [12,13]. This reduction occurs when the fluid temperature in the near-wall region exceeds the pseudo-critical temperature; in this event, the near-wall fluid density decreases sharply, causing local flow acceleration. If the heat-transfer rate is large enough, the flow velocity increases near the wall more than in the low-

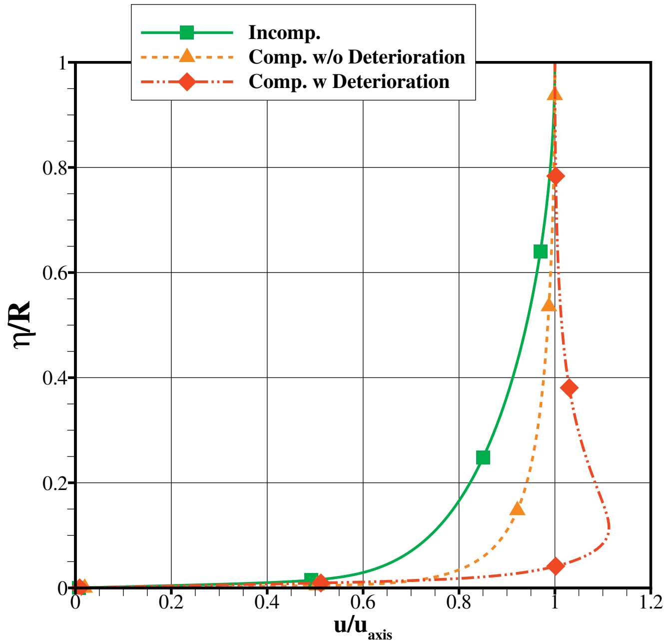

Fig. 5. Axial velocity u distribution along the radius η of a heated tube section for various fluids and flow regimes (data taken from Ref. [14]). Centerline velocity u_{axis} and tube radius R are used to non-dimensionalise the variables and $\eta/R = 0$ at wall.

temperature and high-density core region and thus the velocity profile is modified in such a way that large regions of low shear stress are present. Finally, this gives rise to heat-transfer deterioration. This effect can be emphasised by the presence of buoyancy in upward flows because the high density core region is further slowed down by gravity.

Typical buoyancy-free velocity profiles and associated shear stress distributions in a tube section for different fluids and flow regimes are represented in non-dimensional form in Figs. 5 and 6, respectively. These figures are obtained using a numerical solver of the Reynolds-Averaged-Navier-Stokes equations [14]. In case of incompressible fluid (i.e., constant density), velocity profile does not present any distortion and consequently the shear stress distribution is linear, regardless of the level of the entering heat flux. On the other hand, for a supercritical fluid (i.e., a compressible fluid with large density variations), if the entering heat transfer is large enough, the resulting fluid acceleration implies a velocity profile peak (Fig. 5) and thus a shear stress reduction that can also lead to negative values (Fig. 6). In this case, the loss of turbulent energy is such to induce heat transfer deterioration. In these figures, the intermediate case of a supercritical fluid with moderate heat transfer is also shown: a certain amount of shear stress reduction is present but it is not sufficient to induce deterioration. The described behaviour of the velocity profile has been noticed both experimentally and theoretically by many authors (e.g., [15]). However, in the recognition of the phenomena that characterise the heat transfer to supercritical fluids, literature often ignore that deterioration can be induced not only by the turbulent transport impairment in the core region of the flow, but also by the thickening of the viscous sub-layer close to the wall, which increases the thermal resistance of the whole flow. In Ref. [14], still using a numerical solver of the Reynolds-Averaged-Navier-Stokes equations, it is shown that the latter effect can be of the same order of the turbulent transport impairment described above. Anyway, it is widely recognised that deterioration can be prevented, or at least mitigated, by increasing the pressure level (because the effect of the near-critical region vanishes), and/or the mass flow rate, and/or by decreasing the heat flux. In addition, numerical results have highlighted that surface roughness can substantially prevent heat transfer deterioration even if, of course, a penalty in terms of coolant pressure drop occurs [5].

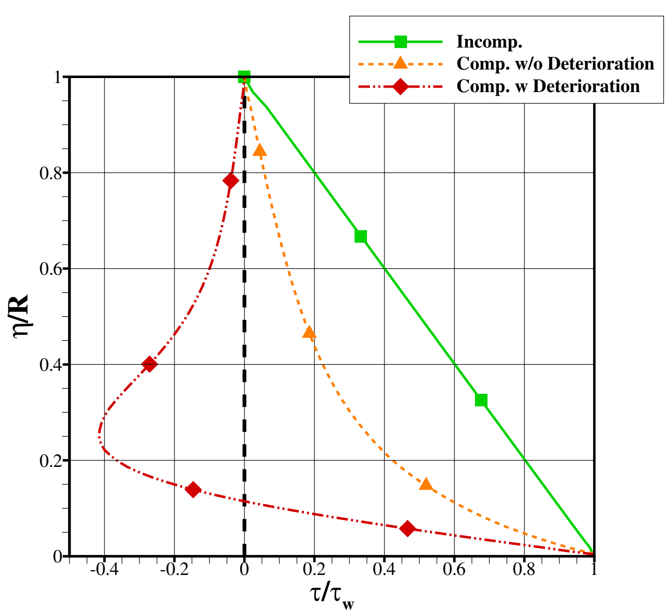

Fig. 6. Shear stress τ distribution along the radius η of a heated tube section for various fluids and flow regimes (data taken from Ref. [14]). Wall shear stress τ_w and tube radius R are used to non-dimensionalise the variables and $\eta/R = 0$ at wall.

4. State of the art

The research on the heat transfer to supercritical fluids has been growing considerably over the years. To give an idea of this increasing interest, Fig. 7 shows the number of issued scientific journal papers per year and having both the keywords “heat transfer” and “supercritical fluid” and, on a separate line, those with the more specific keyword “heat transfer deterioration". The data are taken from Scopus [16], one of the largest citation database of peer-reviewed literature. The total number is more than 700 in the first case and more than 400 in the second case; in both cases, the issued papers per year are growing

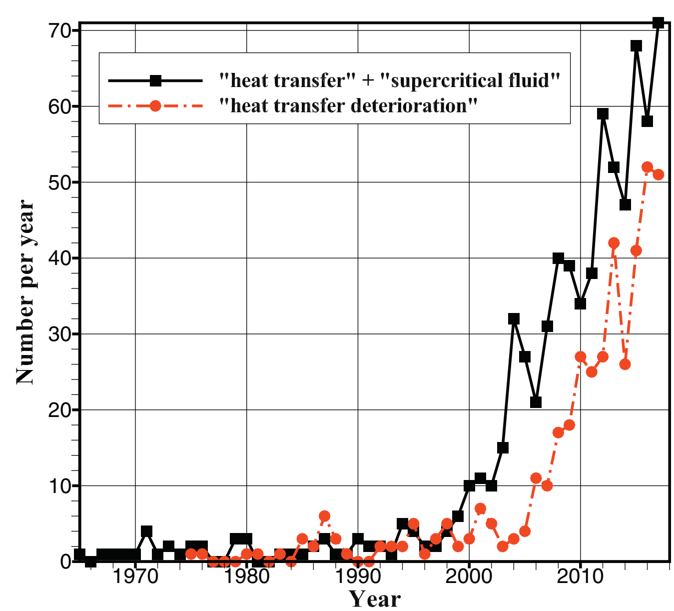

Fig. 7. Number of issued scientific journal papers per year and having the keywords “heat transfer” and “supercritical fluid” -black line- and “heat transfer deterioration” -red line- (data taken from Scopus [16]).

rather regularly. In what follows, the relevant the state of the art is presented, by dividing it into experimental studies and computational studies. The strengths and weaknesses of the currently used approaches are also discussed.

4.1. Experimental studies

Early experimental research on the heat transfer to supercritical fluids was initiated in the 1950s and 1960s by the need to support the thermal design of fossil-fuel power plants and rocket engines operating at supercritical pressure. Results from these early experiments showed very complicated features of turbulent heat transfer to supercritical fluids, especially in upward flows (Section 3). This has prompted the researchers to continue such investigations collecting more data. Since then, a massive number of data, estimated to be tens of thousands, have been collected worldwide, mainly for supercritical water [2] and carbon dioxide [17]. The adopted test setup, generally referred to as “heated tube experiment”, is almost the same for all the test campaigns: a circular cross section tube, which can be long even hundreds of diameters, is electrically heated while a supercritical fluid flows inside. The acquired data are relevant to the inlet and exit pressure and temperature and external surface temperature in various sections of the tube. This experimental set-up permits to estimate the bulk values of Nusselt, Reynolds, Prandtl, and Grashof numbers, which are used to derive heat transfer correlations. Test conditions differ from each other mainly for the adopted fluid, pressure level, fluid mass flow rate, tube radius, and tube orientation with respect to the gravitational field. These studies have permitted to better comprehend the main characteristics of the heat transfer to supercritical fluids. Despite the simplicity of the experimental set-up, the complexity of the problem does not permit to find a single heat transfer correlation able to thoroughly describe the heat transfer to supercritical fluids. This shortcoming is even more evident if heat transfer deterioration occurs. In conclusion, at present, literature offers a large number of heat transfer correlations, each one being “the best” in reproducing the data of a specific experiment but not the data from other experiments. Including more experimental data, which has been occasionally made collecting data from many research groups, has the only effect to dramatically increase the uncertainty of the proposed correlation. For instance, in Ref. [18] a database containing about 12,000 data points from different experiments, mostly for non-deteriorated heat transfer, presents a scattering of 50% with respect to the proposed correlation, as shown in Fig. 8. Such level of uncertainty does not permit any trustworthy prediction of practical interest. The actual scenario seems to be very discouraging and the introduction of new data using the heated-tube experimental apparatus will not progress much the comprehension and quantification of the heat transfer phenomena to supercritical fluids.

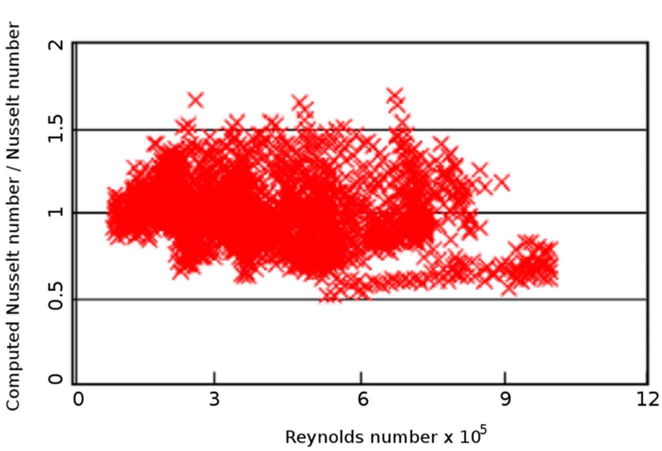

Fig. 8. Ratio of the Nusselt number computed with a typical correlation to the experimental Nusselt number versus Reynolds number (figure taken from Ref. [18]).

Because of the inherent difficulty in finding suitable heat transfer correlations and because the technological devices that make use of the heat transfer to supercritical fluids are far more complex than the heated tube experiments, applied research often verifies the quality of a design by testing the devices of interest under realistic conditions. Traditionally, such analysis are based on an experimental investigation that involves the construction of the device (typically in a reduced scale) and the direct measurement of few performance parameters. In fact, the detailed instrumentation of an industrial device can be extremely time-consuming and expensive. Moreover, if the test fails or the results are not satisfactory, a new design must be conceived and realised for a new test campaign. Optimisation of the design is not possible in this way and generally large margins are employed to guarantee the safety of the device; this leads to non performing designs. Moreover, such devices are typically tested in nominal conditions and few assessments are made in off-nominal conditions, especially because they are not easily predictable. Thus, a design which is considered to be reliable, can result to be inappropriate in conditions far from the nominal one. For instance, an heat exchanger which safely operates at the nominal fluid pressure level, may encounter hazardous heat transfer deterioration if pressure reduces. The direct testing of the actual devices, even if in scale, is typically made by rocket engine manufacturers (e.g., [19]). Consequently, rocket engines are designed with large margins at the expense of reduced mass of the payloads that are embarked in the launch vehicles.

A different and still almost unexplored way to experimentally approach the problem of interest is the analysis of the basic flow phenomena. This can be achieved by means of detailed data including at least velocity and temperature profiles within the flow-field, which play a decisive role for modelling deteriorated heat transfer (Section 3). According to the open literature, only two valuable efforts have been made in this direction: the very seminal work of Wood and Smith [20] and the one of Kurganov and Kaptil’ny [15]. Both experiments consisted in a heated tube equipped with a moving probe inside, which was able to measure the local temperature and streamwise velocity at different distances from the wall using a small Pitot tube and a microthermocouple. Using this technique, the main phenomenology occurring in case of heat transfer deterioration, i.e., the distortion of the radial velocity profiles (Fig. 5), has been pointed out. However, measurement accuracy can be impaired because of the use of a bulky probe immersed in the flow-field. Moreover, only one measure can be acquired at a time and only for a single channel section. Using this technique, it is very difficult to have a thorough mapping of the flow-field and only steady-state measurement can be acquired. Consequently, estimation of the turbulence fluctuations and statistics, which are essential variables to deeply focus the flow transport phenomena, are not possible. The only documented effort with non-intrusive techniques able to overcome this limitation has been made using a Lased-Doppler-Velocimetry (LDV) system, in a facility having the capability of optical access for local measurements of turbulent velocity of supercritical water [21]. The most relevant shortcomings of that setup are the inability to measure the fluid temperature, the inability to perform measurements in more than one location at a time, which is inherent to LDV systems, and, even more important, the inability to make accurate measurements when temperature is high, as in the case of heat transfer deterioration. However, it should be noted that detailed experiments on the heat transfer to supercritical fluids represent a challenge for any experimentalist because the involved high pressure and temperature do not easily permit to properly instrument the test article.

4.2. Computational studies

With the advancement of the computing performances, Computational Fluid Dynamics (CFD) has become a common practice in science and engineering. Nowadays, especially considering massive parallel computing, it is possible to study complex turbulent flow-fields in full-scale using numerical solvers of the Reynolds-Averaged Navier-Stokes equations (RANS) and eventually, especially at reduced-scales, using solvers based on Large Eddy Simulation (LES). Finally, simplified flow-field configurations, especially at low-to-moderate Reynolds number, can be scrutinised with Direct Numerical Simulation (DNS), that is, without any necessity of modelling the turbulent transport. Each kind of solver presents its own strengths and weaknesses and is therefore complementary to the others. In fact, while DNS provides very detailed insight into the physics of fluid-dynamics at the cost of large computing resources which limits its application to basic studies, RANS is far less computationally expensive although turbulence needs to be modelled. The characteristics of the LES approach are in between those of DNS and RANS, as it requires turbulence modelling only for the smallest flow scales and thus permits analysis of more practical problems than using DNS. Since the late 90s, the pressing necessity to predict the heat transfer within the technological devices that make use of supercritical fluids has prompted the researchers to develop more and more accurate RANS solvers able to describe such flow fields. Two families of analysis are generally made by this community: two-dimensional axi-symmetric simulations, with the double intent to provide a better understanding of the turbulent heat-transfer mechanism and to go beyond the massive and often incoherent experimental data produced with heated-tube experiments (e.g. [22-24]); and, more recently, three-dimensional simulations of actual devices like heat exchangers and cooling systems (e.g. [25,26,5]). These studies have demonstrated that the numerical predictions of wall temperature and heat transfer coefficient are in good agreement with the experimental data, mainly for the normal and enhanced heat transfer cases. Moreover, the adopted turbulence models are, to some extent, able to reproduce the effects of buoyancy and/or thermal acceleration when heat transfer deterioration occurs, even if the performance of these turbulence models varies significantly in predicting the onset of such effects. At last, no clear conclusion can be drawn on which turbulence model is superior to others. Considering more refined modelling than RANS, CFD of supercritical fluids is generally addressed to the problem of coaxial-jets mixing and combustion, using LES solvers for full-scale geometries (e.g. [27-29]) and DNS solvers for basic setups (e.g. [30]). This challenging problem presents major differences with respect to the problem of heat transfer to supercritical fluids; in fact, the turbulent phenomena involved in wall-bounded flows, are substantially different from the turbulent phenomena that occur in unbounded jets. For this reason, the methodologies and results relevant to supercritical jet mixing and combustion cannot be easily extended to the problem of interest. Very few studies using LES and DNS have been reported for supercritical heat transfer problems. This shortage appears to be closely linked to the lack of detailed experimental data described above. According to the open literature, Refs. [31-33] are the only ones presenting LES and DNS solutions. In particular, Ribert et al. [31] have presented very preliminary LES results whose final intent is the description of rocket engine cooling channel flows of supercritical hydrogen. Bae et al. [32] have performed DNS of the approximated Navier-Stokes equations under the hypothesis of low-Mach-number for supercritical carbon dioxide flows within a heated tube, which is 30 diameters long, and with an inlet Reynolds number Re equal to 5400(which corresponds to a friction Reynolds number Re_τ equal to 180). Moreover, the fluid thermodynamic properties are evaluated for a single pressure level; in case of large pressure variations, as in long heated tubes, this hypothesis is strongly questionable because of the strong pressure dependence of the fluid properties in the near critical region. Finally, the recent DNS analysis of Kawai [33] refers to a boundary layer of supercritical hydrogen with Re_τ up to 390. Unfortunately, the use of constant temperature (instead of constant heat flux) as wall boundary condition does not permit to investigate the heat transfer deterioration.

5. Conclusions

The present review presents the status of the research on the heat transfer to supercritical fluids, with particular focus on the phenomenon of heat transfer deterioration. The analysis of both the experimental and computational studies presented in the open literature highlights that:

- despite the large efforts made by the scientific community, the challenging problem of heat transfer to supercritical fluids is far from being fully comprehended, especially in case of heat transfer deterioration;
- heated-tube experiments are commonly performed but they do not advance much the comprehension and prediction of the phenomena;
- no single heat transfer correlation has been found to properly describe the problem of interest;
- non-intrusive and accurate measurements of the flow-field (average and instantaneous fields of velocity and temperature) have never been carried out;
- performance of the turbulence models used in RANS solvers varies significantly in predicting the heat transfer deterioration and its onset;
- numerical insight of the problem using LES and DNS is still almost unexplored.

In conclusion, since the poor comprehension and prediction of the phenomena related to the heat transfer to supercritical fluids may limit the development of future applications (e.g., Supercritical Water-Cooled Nuclear Reactors and Oxygen-Methane Rocket Engines), new research approaches are highly needed. In particular, combined experimental-computational approaches may provide a wealth of information at a resolution that is well above what has been ever achieved, permitting to shed new light on the problem of heat transfer to supercritical fluids, with special regard to the heat transfer deterioration.

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