Chapter 16

SUMMARY

The following is a summary of the main findings of this study:

- There is a plethora of data, empirical correlations and simple models for heat transfer and pressure drop published in the literature on the use of many supercritical fluids, mainly for simplified test sections. We have compiled and reviewed as much of the information as possible (in general, about 650 literature sources), and have provided all the key references and inter-compared the experimental and theoretical approaches. The data largely cover all the ranges of interest, but of course for mainly commercial reasons some design specific information is missing from the open papers and reports.
- There are hundreds of fossil power plants in the world using supercritical conditions (thermal parameters: water pressure of up to 25 – 30 MPa, turbine inlet temperatures of up to 625°C (but mainly lower than 600°C) and power output of up to 1400 MW_e), which have been successfully operated for many years. Their main advantage is high thermal efficiency of up to 45% – 53%. The demonstrated experience in their design and operation is very helpful for current developments in fossil-fired units and in nuclear-powered reactors cooled with supercritical water and provides useful benchmark data.
- After a 30-year hiatus, because of the fossil experience and the need to improve the overall cycle thermal efficiency, the idea of developing nuclear reactors cooled with supercritical water became attractive again, and several countries (Canada, Germany, Japan, Russia, and the USA) have started to work in that direction. However, none of these concepts is expected to be implemented in practice before 2015 – 2020.
- The major limits in designing supercritical heat-transfer systems seems to be with the materials reliability and corrosion rates at high temperatures, pressures, and for nuclear systems with neutron fluxes, within a highly aggressive medium such as supercritical water. The combined effect of these parameters is yet to be fully defined and investigated.

- Heat transfer at supercritical pressures is strongly influenced by the significant and rapid changes in thermophysical properties at these conditions near the critical point. For many working fluids that are used at supercritical conditions, their physical and thermophysical properties are well established and available via the ASME tables and NIST computerized tabulations. All thermophysical properties undergo significant changes near the critical and pseudocritical points. In the vicinity of pseudocritical points with an increase in pressure, these changes become less pronounced. In general, density and dynamic viscosity undergo a significant drop within a very narrow temperature range, while specific enthalpy and kinematic viscosity undergo a sharp increase. Volume expansivity, specific heat, thermal conductivity, and Prandtl number have a peak near both the critical and pseudocritical points. The magnitudes of these peaks decrease very quickly with an increase in pressure. The heat transfer and pressure drop show corresponding variations. However, satisfactory analytical methods have not yet been developed due to difficulty in dealing with the steep property variations, especially in turbulent flows and at high heat fluxes.
- The majority of the experimental studies deal with heat transfer and relatively few with hydraulic resistance of working fluids, mainly water, carbon dioxide, and helium, in circular tubes. A limited number of studies were devoted to heat transfer and pressure drop in annuli, rectangular-shaped channels and bundles (just two such data sets have been found so far). In general, experiments at supercritical pressures are very expensive and require sophisticated equipment and measuring techniques. Therefore, some studies (for example, heat transfer in bundles) are proprietary and hence remain unknown or are not published in the open literature.
- In general, experiments showed that there are three modes of heat transfer somewhat loosely defined in fluids at supercritical pressures: (1) normal heat transfer, (2) so-called deteriorated heat transfer with lower values of the HTC (and hence higher values of wall temperature) than those for (1) within some part of a test section; and (3) relatively increased or improved heat transfer with higher values of the HTC within some part of a test section. We give a more precise definition based on the relative magnitudes of the HTCs. The deteriorated heat transfer is of limited extent, usually appears at high heat fluxes and low mass fluxes in simple tubes, and is generally considered to be due to buoyancy forces dominating the formation and behavior of the heat transfer boundary layer near the heated wall. Importantly, this decreasing HTC phenomenon can be entirely suppressed or significantly offset by increasing the turbulence level with flow obstructions and other heat-transfer enhancing devices.
- In consequence of the above, the limited region of deteriorated heat transfer has not been detected in bundles cooled with supercritical water, as based on the only two available references.
- There are many heat-transfer correlations (empirical fits to data) obtained at various supercritical conditions, which describe heat

transfer mainly in circular tubes and similar simple flow geometries. A comparison of these correlations showed that several of them can be used for preliminary estimations of HTC. However, no one correlation is presently able to completely describe deteriorated heat transfer.

- There exists a single correlation suitable for heat-transfer calculations in water at supercritical pressures flowing in reactor bundles. The Dyadyakin-Popov (1977) correlation was obtained in water at supercritical pressures flowing in a short tight finned bundle and hence is not suitable for other types of bundles.
- While useful progress has been reported on scaling heat transfer between different fluids using dimensionless groups. Scaling parameters should be selected and used with caution. In general, they can be used for scaling operating conditions from one fluid to another just for comparative reference purposes. Due to scaling parameters simplicity, the special behavior of thermophysical properties at supercritical pressures and complexity of the processes involved, causes some discontinuities to exist.
- There are considerably fewer publications related to hydraulic resistance at supercritical pressures than on HTC (about 30 papers). According to some of the cited literature sources, the hydraulic resistance of an isothermal turbulent flow of fluid at the near-critical state follows the same trends as that at subcritical pressures in smooth tubes.
- There is no one correlation suitable for hydraulic-resistance calculations in water at supercritical pressures flowing in heated bundles. The Dyadyakin-Popov (1977) correlation was obtained in water at supercritical pressures flowing in a short tight-finned bundle.
- Because supercritical fluids are thermally expandable, and the flow and pressure-drop multiple values for a given heating profile, the flow can be unstable in certain regions. Hence, the heat transfer and hydraulic resistance at supercritical pressures can be accompanied by flow oscillations and other instabilities at some operating conditions. However, experimental data on these aspects remains very limited.