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Review

# A brief review on convection heat transfer of fluids at supercritical pressures in tubes and the recent progress

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## HIGHLIGHTS

- Convection heat transfer at supercritical pressures.
- Review and recent progress.
- Thermophysical properties at supercritical pressures.
- Heat transfer deterioration.
- Buoyancy criterion.

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## ABSTRACT

This study presents a state-of-the-art overview on heat transfer characteristics of fluids (mainly water, carbon dioxide and hydrocarbon fuels) flowing in smooth tubes and enhanced tubes at supercritical pressures and tries to obtain a fundamental understanding of the unique characteristics. Heat transfer in enhanced tubes is much better than that in smooth tubes with a larger pressure drop penalty at supercritical conditions. Thermo-physical properties of fluids at supercritical pressures and relevant parametric effects (e.g., effects of mass flux, heat flux, pressure and flow direction) on heat transfer performance are outlined. Inconsistencies in the literature on heat transfer are emphasized and evaluated. Possible reasons are suggested to explain those inconsistencies. Moreover, the mechanisms for heat transfer deterioration at supercritical pressures are discussed and different correlations for predicting heat transfer deterioration are compared and assessed with experimental data. These predictive correlations based on one working fluid cannot be applied directly to other working fluids. Besides, several common buoyancy criteria proposed in the literature to distinguish forced convection and mixed convection are evaluated and show large discrepancies with experimental data. There is no buoyancy criterion developed for hydrocarbon fuels. Future research needs are warranted for heat transfer of near-critical and supercritical fluids.

## Contents

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## Nomenclature

| | |
|---|---|
| $Bo^*$ | Buoyancy number, $Gr^*/(Re^{3.425}Pr^{0.8})$ |
| $c_p$ | specific heat, J/(kg K) |
| $e$ | ratio of rib pitch to height |
| $d$ | diameter, m |
| $G$ | mass flux, kg/(m$^2$ s) |
| $g$ | acceleration of gravity, m/s$^2$ |
| $Gr$ | Grashof number, $g\beta d^3(T_w - T_f)/\upsilon^2$ |
| $Gr^*$ | Grashof number, $g\beta d^4 q_w/(\lambda\upsilon^2)$ |
| $H$ | enthalpy, J/kg |
| HTC, $h$ | heat transfer coefficient, W/(m$^2$ K) |
| HTD | heat transfer deterioration |
| HTE | heat transfer enhancement |
| $K_v$ | acceleration parameter, $4q_w\beta/(\rho u c_p Re)$ |
| $m$ | mass flow rate, kg/s |
| $Nu$ | Nusselt number, $hd/\lambda$ |
| $P$ | pressure, Pa |
| $Pr$ | Prandtl number, $c_p\mu/\lambda$ |
| $q$ | heat flux, kW/m$^2$ |
| $Re$ | Reynolds number, $Gd/\mu$ |
| $T$ | temperature, K |
| $u$ | velocity, m/s |

*Greek symbols*

| | |
|---|---|
| $\beta$ | volumetric coefficient of expansion, 1/K |
| $\lambda$ | thermal conductivity, W/(m K) |
| $\mu$ | dynamic viscosity, Pa s |
| $\upsilon$ | kinematic viscosity, m$^2$/s |
| $\rho$ | density, kg/m$^3$ |

*Subscripts*

| | |
|---|---|
| $c$ | critical |
| $f$ | bulk fluid |
| pc | pseudo-critical |
| th | threshold |
| $w$ | wall |

## 1. Introduction

Since Schmidt et al. [1] investigated the heat transfer characteristics of fluids near the critical point and found that the heat transfer coefficient (HTC) of near-critical-point fluid was much higher than that at subcritical pressures, researchers have begun to widely investigate the heat transfer performance of supercritical fluids [2–9].

In the 1950s, supercritical water ($T_c$ = 374.14 °C, $P_c$ = 22.12 MPa) was used in steam generators to improve the thermal efficiency of fossil-fired power plants. In the early 1960s, supercritical water was adopted as coolant in nuclear reactors. The main advantages by using supercritical water in nuclear reactors are the enhanced thermal efficiency due to high operating temperature and the reduced operational cost due to eliminated steam separators, steam generators and steam dryers, etc. The thermal efficiency can be increased from 33–35% to about 45% by using supercritical water. Therefore, a large number of experimental and numerical investigations on supercritical water were conducted in the literature [10–38]. Recently, the potential of supercritical fluids for biodiesel production has been discussed [39,40]. Supercritical water was used as reaction medium for hydrogen production from biomass gasification [41] and for glycerol reforming (the main by-product of biodiesel production) [42]. However, the high operating cost limits the development of this technology. Another working fluid, $CO_2$, is also widely investigated in many areas such as advanced nuclear power plants, high temperature solar power stations, Enhanced Geothermal System (EGS) with $CO_2$, and $CO_2$ sequestration. Thus carbon dioxide has become the most investigated fluid at supercritical pressures besides water [43–63]. The critical pressure ($P_c$ = 7.38 MPa) and temperature ($T_c$ = 31.05 °C) of $CO_2$ is relatively low and thus the operating cost is reduced. $CO_2$ can also be used in applications such as two-phase flow characterization [64] and in-tube cooling of $CO_2$-lubricating oil mixtures [65]. Refrigerants, such as R134a and R22 are also used as working fluids at supercritical pressures [66,67]. Convection heat transfer of hydrogen and helium at supercritical pressures has also been investigated widely [68,69].

On the other hand, the interest on heat transfer characteristics of hydrocarbon fuels at supercritical pressures is increasing due to the development of advanced hypersonic aircraft, rocket and missile engines, etc. Thermal management is a big challenge at these areas. To improve the cooling capacity, the regenerative cooling system where engine fuel (e.g., RP-3 aviation kerosene) works as coolant and travels through the cooling tubes along the chamber wall was developed as an effective thermal management technique [70–72]. As the pressures in the cooling channels are generally higher than the critical pressure of hydrocarbon fuels and the fuel temperature ($T_f$) gradually increases by absorbing the heat generated from the chamber wall, $T_f$ may pass the critical temperature and finally the fuel becomes supercritical [73]. As the changes in thermo-physical properties of supercritical hydrocarbon fuels might enhance the heat transfer significantly, many studies have focused on the heat transfer of hydrocarbon fuels at supercritical pressures [74–86].

At supercritical pressures, heat transfer enhancement (HTE) or heat transfer deterioration (HTD) can occur side by side. The transition might be very abrupt. Thus the HTD phenomenon has also received continuous interest. HTD might be due to the variation of thermo-physical properties as well as the effects of buoyancy force and flow acceleration. Researchers have proposed many correlations to predict the onset of HTD, however, a general correlation has not been obtained yet.