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Non-dimensional parameters for static instability in supercritical heated channels

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ABSTRACT

A study of supercritical flow stability in vertical channels has been undertaken to develop and assess relevant non-dimensional parameters governing the static instability mode. As in two-phase flow, two types of flow instabilities have previously been identified: static and dynamic. However, in supercritical flow, it was found that static instability and dynamic instability occurs in different temperature ranges. For a given fluid and system pressure, below a certain temperature only a static instability is possible, while above that temperature only a dynamic instability is possible. In down-flow, the static mode is more prevalent, while the dynamic mode was found to be more prevalent in up-flow. The examined fluids were H_2O and CO_2. This paper proposes and assesses new non-dimensional parameters for static instability in supercritical fluid flow, as well as assesses the non-dimensional parameters of Ambrosini. Different inlet temperatures, inlet and outlet *K* factors and systems pressures were examined. Insights into how the instability can be delayed or circumvented were obtained and are discussed. This study was undertaken using an in-house linear instability program.

1. Introduction

Supercritical light water is the proposed primary coolant for the new Generation IV nuclear reactor being designed in Canada where outlet temperatures can exceed 600 °C. A core design being considered by Atomic Energy of Canada (AECL) involves vertical down-flow with inlet temperature ~350 °C. Higher thermal efficiency is a perceived advantage of the supercritical pressure design, while corrosion and flow instabilities are limiting concerns. The stability characteristics of vertical down-flow systems have not been studied or reported by other investigators, partly because it had not been considered seriously by designers until now.

Flow stability of a system operating in the supercritical pressure and temperature range has become an active research topic among researchers today. Unsteady or oscillatory flow-rate in a reactor core is undesirable as it can cause inadequate cooling of the fuel bundles and, in the extreme case, overheating and/or meltdown. The first in-depth analytical study of the various supercritical flow instability modes was reported by Zuber [1]. He showed that supercritical flow, like two-phase flow, can exhibit flow oscillations and instabilities. Ambrosini [2] has reported, after doing extensive analyses, that supercritical flow instability is similar to two-phase flow instability in many respects.

Static instability in supercritical flow were reported by Ambrosini and Sharabi [3], followed by Shah [4] and Chatoorgoon [5]. Ambrosini and Sharabi [6,7] studied vertical up-flow in heated channels at supercritical pressures using the Relap code and presented a universal set of non-dimensional parameters relevant to supercritical flow dynamics. Ambrosini's non-dimensional parameters [3,7] were based on drawing similarities between two-phase flow and supercritical flow. Chatoorgoon [8] studied oscillatory flow instability in two horizontal parallel channels. Ortega Gomez et al. [9] studied the thermal-hydraulic stability of uniformly heated channel at supercritical water pressure and also proposed non-dimensional parameters. However, these parameters are specific to H_2O and are, therefore, inapplicable to other fluids in their present form.

Presented herein are non-dimensional parameters for the static instability boundary in supercritical flow in parallel channels. Unlike Ambrosini's parameters [3,7], which are universal parameters for any dynamic flow situation and are not restricted to the flow instability boundary, the parameters presented here are specific to the flow instability boundary in supercritical parallel channel flow and, therefore, are not meant to be used outside their intended application. However, these parameters do have some advantages that may be useful to engineers, one of which is a relatively simple way of assessing flow stability in a heated channel without the need for a formal stability analysis and the reliability of transferring instability data of one fluid to another fluid in the same geometry.

Furthermore, there has been no reported study of flow instability in down-flow channels; this is another reason for this study.

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Nomenclature

A	flow area [m^2]
C_K	friction loss factor in momentum equation [m^{-1}]
g	gravitational constant [m/s^2]
G	mass flux [kg/m^{2}s]
h	enthalpy [kJ/kg]
K_{IN}	channel inlet *K*-factor loss [-]
K_{OUT}	channel outlet *K*-factor loss [-]
N_{SPC}	Ambrosini's non-dimensional sub-pseudo-critical number [-]
N_{TPC}	Ambrosini's non-dimensional trans-pseudo-critical number [-]
Q	applied power [kW]
g	gravitational constant [m/s^2]
G	mass flux [kg/m^{2}s]
h	enthalpy [kJ/kg]
K_{IN}	channel inlet *K*-factor loss [-]
K_{OUT}	channel outlet *K*-factor loss [-]
N_{SPC}	Ambrosini's non-dimensional sub-pseudo-critical number [-]
P_{o1},P_{o2}	stagnation pressure in inlet, outlet plenum, respectively (Pa)
Q_s	power at instability boundary [kW]
Q_p	power required to achieve $\frac{\partial\Delta(p+\rho u^2)}{\partial G}=0$ at the given flowrate [kW]
T_{IN}	channel inlet temperature [°C]
T_{OUT}	channel outlet temperature [°C]
$\hat{Q}$	non-dimensional power in Chatoorgoon's model
ξ	non-dimensional pressure-drop parameter in Chatoorgoon's model
ρ_e	channel outlet density [kg/m^3]
ρ_i	channel inlet density [kg/m^3]

Some limited horizontal flow and up-flow cases are included for comparison purposes.

2. Rationalization and problem definition

A valid set of non-dimensional parameters would have far-reaching consequences to the design engineer as they would facilitate applying data obtained from one fluid to another fluid with good engineering accuracy. It is often much cheaper to perform instability experiments with a fluid that has a significantly lower critical pressure and temperature. For example, it is not uncommon to use CO_2 to simulate supercritical H_2O behaviour. Thus, a valid methodology for applying data from CO_2, say, to H_2O without loss of accuracy would be extremely beneficial to the design engineer.

Canada's GenIV design is considering one option where the channel flow is downward as this arrangement would allow easy re-fuelling, which must be done from the inlet side, to take place without shutting down the reactor. Thus, it is necessary to determine if the non-dimensional parameters proposed to date are applicable for heated down-flow and if they perform well enough to make transferring data obtained with one fluid to another with sufficient engineering certainty. Experiments are presently being conducted with CO_2.

It is unimportant, really, which geometry is chosen for this numerical study. Hence, the geometry considered first by Ambrosini and Sharabi [3] is adopted again, while the fluids chosen for assessing the non-dimensional parameters are CO_2 and H_2O, for reasons already stated.

The simple geometry considered, Fig. 1, consists of a single vertical pipe channel of length equal to 4.2672 m, ID = 8.36 mm, $\varepsilon = 2.5 \times 10^{-5}$ m. A variety of different inlet and outlet *K*-factors were employed. For water, pressures of 25, 30 and 40 MPa were used, while 8 MPa was used for CO_2. Solutions were generated for situations of no inlet and outlet plena as well as for with inlet and outlet plena.

3. Theory for static instability in supercritical flow

3.1. 3.1Channel without inlet–outlet plena

Developed in this section are non-dimensional parameters for static instability in supercritical heated channel flow without inlet–outlet plena. In Section 3.2 the case of a heated channel with inlet–outlet plena is considered.

For the case of two-phase flow in heated channels, Rohatgi and Duffey [10] applied the condition $\partial\Delta p/\partial\Delta G = 0$ on the flow instability boundary, where Δp is the channel static pressure drop. A quadratic form for the instability limit for homogenous equilibrium flow in parallel channels was derived. For static instability of supercritical flow in horizontal heated channels, Chatoorgoon [5] reported finding

$$\frac{\partial\Delta p_{f,ch}}{\partial G} = 0 \qquad (1)$$

to approximate the flow-rate at the instability boundary. $\Delta p_{f,ch}$ is the channel frictional pressure drop while G is the mass flux. For horizontal flow (i.e. no gravity), the steady momentum equation will confirm that Eq. (1) is mathematically equivalent to

$$\frac{\partial\Delta(p+\rho u^2)_{ch}}{\partial G} = 0 \qquad (2)$$

While Eqs. (1) and (2) are mathematically identical for horizontal flow, they are not identical when gravity effects are present. For vertical flows Eq. (2) is deemed more appropriate because it includes gravitational effects. Hence, Eq. (2) is employed forthwith as the condition for static instability in supercritical flow and the flow rate that satisfies Eq. (2) is deemed a very good approximation of the static instability boundary flow rate, for a given channel power.

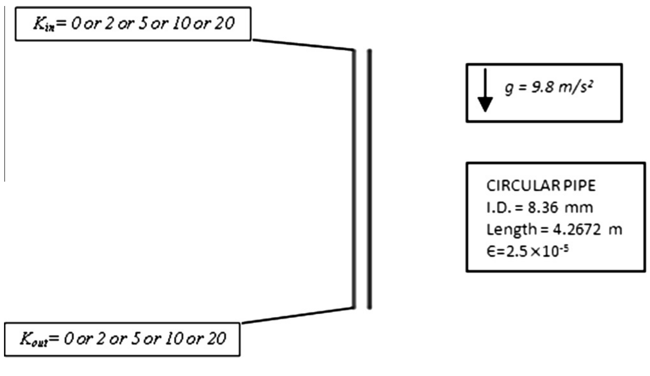

Fig. 1. Schematic of geometry studied.