Experimental Study of Water Flow at Supercritical Pressures

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Abstract

Future supercritical water cooled nuclear reactors will operate at a coolant pressure close to 25 *MPa* and at outlet temperatures ranging from 500°*C* to 625°*C*, i.e., above the critical pressure and temperature of the water (22.06 *MPa* and 373.95°*C*, respectively). Using coolant pressures higher than critical values, avoid boiling and eventual critical heat flux to occur. In addition, the outlet flow enthalpy in these reactors will be much higher than those of actual ones. Consequently, the increase of this thermodynamic property should permit overall nuclear plant efficiencies of up to 48% to be achieved. However, under such flow conditions, thermalhydraulics behaviors of supercritical water are not fully known, i.e., pressure drop, forced convection and heat transfer deterioration, critical and blow down flow rate, etc. Up to now, only a very limited number of studies in these areas have been performed. In particular, the knowledge of critical (choked) discharge of supercritical fluids is mandatory to perform nuclear reactor safety analyses and to design key mechanical components (e.g., control and safety relief valves, etc.). Nevertheless, existing choked flow data have been collected from experiments at atmospheric discharge pressure conditions and in most cases by using working fluids different than water. For this reason, an experimental supercritical water facility has been built at École Polytechnique de Montréal. In this paper, preliminary results obtained using this facility are presented and discussed.

Keywords: *supercritical water cooled reactor, supercritical water, choked flow, pseudo-critical temperature.*

1. Introduction

During the last 20 years, the world energy needs have been continuously increasing at very high pace. It is obvious that to satisfy future world energy requirements the nuclear industry should play an important role. Canada has largely contributed in different research and development (R&D) programs that permitted the national nuclear industry to continue growing. In a long term perspective, Canada has signed the GIF Generation IV international agreement in July 2001 to participate in the development of new nuclear technologies for the future. Different technologies were proposed by the Generation IV International Forum.[1,2] Within this framework, Super Critical Water-cooled Reactors (SCWR) appears as the foremost candidate of future nuclear power plants to be built by the year 2040. Consequently, in Canada the SCWR technology will replace actual Generation III or advanced

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CANDU nuclear reactors. Canada has more than 40 years of successful experience in the construction and operation of CANDU reactors. This valuable engineering knowledge, combined with the actual know-how of supercritical water fossil-fired power plants, can be implemented together for designing future Canadian SCWR's.

Among the advantages of fuel economy and plant engineering simplifications [3-6], the SCWR technology must also permit the overall thermal efficiency to be increased by up to 15 points of percentage with respect to existing nuclear power plants. Furthermore, for a given thermal power the coolant mass flow rate decreases with increasing the outlet enthalpy. Consequently, the water inventory of SCWR's will be low and will require less pump power. Operating above critical water pressure conditions will eliminate phase changes which must permit a simplification of reactor design to be achieved (i.e., remove steam generators and moisture separators, etc.) However, beside these advantages, some fundamental aspects must be further studied to design SCWRs. For instance, the thermalhydraulics behavior of future nuclear fuel channels can be very sensitive to both the coolant pressure drop and the heat transfer along fuel bundles. In fact very limited information exists in the open literature concerning supercritical-water frictional pressure drop; therefore, additional experiments are mandatory. [2] Due to the fast change in fluid properties occurring around pseudo-critical conditions, most existing correlations are not able to reproduce the experimental trends. It has been observed that a significant decrease on fluid thermal capacity occurring beyond the critical point causes deterioration on heat transfer conditions and consequently, for high heat fluxes, such a situation may compromise the integrity of the nuclear fuel. Since SCWR's will use reduced coolant inventories, the prediction of flow behavior during a loss of coolant accident become fundamental for the correct estimation of depressurization during transients. Understanding the physics of this aspect is also crucial to perform reactor safety analyses and to design hydraulic components and safety relief mechanisms. From a safety view point, experimental and analytical studies are necessary to estimate the discharge of supercritical water during an anticipated transient without scram event and during the eventual occurrence of pipe breaks. Up to now, existing discharge flow data have been collected from experiments at atmospheric discharge pressure conditions and in most of the cases by using working fluids different than water. [4-8] It must be pointed out that keeping the discharge pressure at a unique value (i.e., atmospheric) makes it very difficult to determine whether or not the flow reaches the speed of sound. [2-4] To overcome some of these drawbacks, in this paper a supercritical water experimental set-up coupled with a medium-pressure steam-water loop has been used to perform choking flow experiments. This facility, designed and constructed at École Polytechnique is partially shown in Figure 1. It allows supercritical-water flow conditions of up to 31 *MPa* and 570°*C* to be achieved. The medium-pressure loop, not shown in the figure, permits the back pressure at the discharge of a test section to be varied and kept constant from atmospheric pressure to up to 4.0 *MPa*. Preliminary results obtained from experiments performed using a test section that contains a 1 *mm* diameter, 3.17 *mm* long orifice plate with chamfered edges are presented.

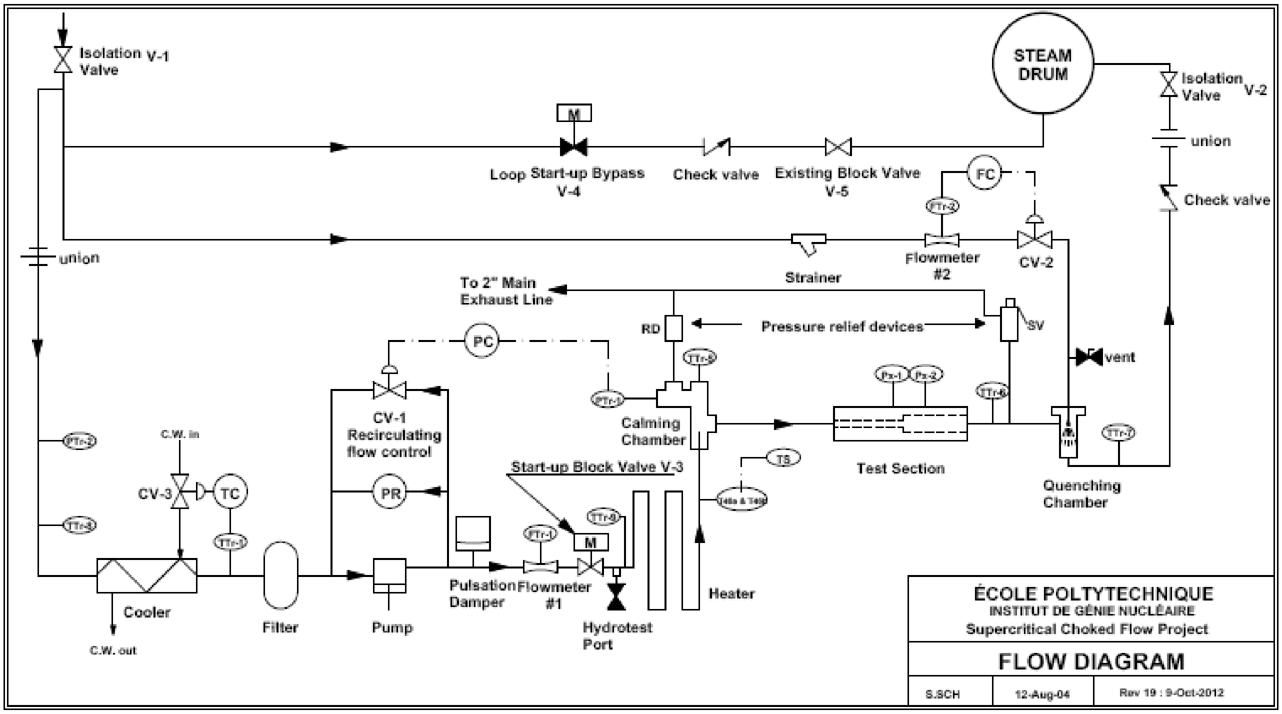

Figure 1. Portion of the supercritical-water experimental facility.

2. Experimental Facility

A portion of the flow diagram of the supercritical water flow experimental facility is shown in Figure 1. It is coupled to a medium-pressure steam-water loop not shown in the figure. Both systems use demineralized distilled water without chemical treatment. The supercritical portion of the facility permits supercritical water conditions to be achieved and carefully controlled. It consists of heat exchangers, a water filter, a six piston reciprocating pump, a pulsating damper and a heater element where supercritical water conditions are achieved, a test section and a quenching chamber. In addition, other components are also used to measure and to control desired flow operation conditions.

Since the discharge pressure is determined by the pressure controlled in the medium-pressure steam-water loop, (i.e., it can be between 0.1 to 4.0 *MPa*) the water temperature at the inlet of the reciprocating pump will be much higher than the maximum value of 65^oC which is recommended by the manufacturer of the pump. Therefore, dual tube heat exchangers are used to bring the coolant inlet temperature below the recommended value. Furthermore, this pump can not accept solid particles dispersed in the water bigger than 5 μm; thus, a glass fiber filter is used to protect it.

It is well known that positive displacement pumps tend to produce flow and pressure fluctuations. To damp eventual pressure oscillations and to avoid possible harmful effects during the experiments, a pulsation damper is installed at the outlet of the pump. This unit reduces the pulsations below ±1% of the pump discharge pressure. For its operation, the damper uses a counter balance pressure of 2800 *psi* of nitrogen (see Figure 1). After the pulsation damper, the water passes through a

"Flow Technology" turbine-type flow meter connected to a National Instruments® data acquisition system. The accuracy of the flow measurement system (i.e., flow meter, frequency to current converter, lineariser, amplifier and data acquisition) is better than 0.5% of the readings.

As shown in Figure 1, supercritical water conditions are reached in an 11.2 *m* Hastelloy C-276 tubular heater element heated by Joule effect using a 550 *kW* DC power supply. The branches of the heater are connected electrically in parallel where the electrical potential is applied to the end of each tube by using 5000 *Amps* nickel plated copper clamps. The electrical connections are arranged in such a way that both inlet and outlet ends of the heater are at ground electrical potential (i.e., the same as the rest of the loop.) The applied thermal power is determined from the measurements of the electrical potential and the electrical current which is measured using two separate instruments, i.e., a 5000 Amps class 0.5 electrical shunt and a Hall effect 5000-LEM unit. Further, the heater is instrumented with 25 spot welded type-K thermocouples located at different axial locations. Additional six thermocouples are installed at radial and axial locations inside the thermal isolation jacket to determine heat losses. The instrumentation is connected to the National Instruments data acquisition and control system via galvanic isolation amplifiers. In is important to mention that the entire facility also accounts with additional 200 *kW* of thermal power to produce the necessary steam in the medium-pressure loop and thus, to control the discharge pressure at a desired value.

Since supercritical fluids tends to became stratified [9,10], a calming chamber (see Figure 1) is installed just upstream of the test section. Inside the calming chamber the supercritical fluid is stirred before entering into the test section. This process avoids flow stratification and permits a better value of the mean fluid temperature to be measured using the thermo well TTr-5 shown in the figure. It is important to mention that before starting the experiments, the calibration of pressure transducers, thermocouples, flow meters and control valves are verified in place using specialized calibration units available in the laboratory. [11]

2.1 The Test Section

The experiments presented in this paper were carried out using a test section having a 1 *mm* diameter and 3.17 *mm* long orifice plate with chamfered edges. Figure 2 shows the schematic of the test section manufactured from a solid Hastelloy C-276 cylinder using the electro discharge method. After its construction, the orifice was carefully measured with a precision higher than +/- 0.001 *mm*. The test section is connected to the loop using 9000 *psi* "Autoclave" Hastelloy unions. As shown in the figure, the test section is instrumented with three pressure taps located upstream and five located downstream of the orifice. Pressure lines are used to connect these taps with pressure measurement panels containing four "Sensotec" 0.1% full scale accuracy absolute pressure transducers to determine flow pressure profiles upstream and downstream of the orifice. It must be pointed out that the measurement of the downstream pressure profile is essential to determine whether or not choking flow conditions are achieved during the experiments.

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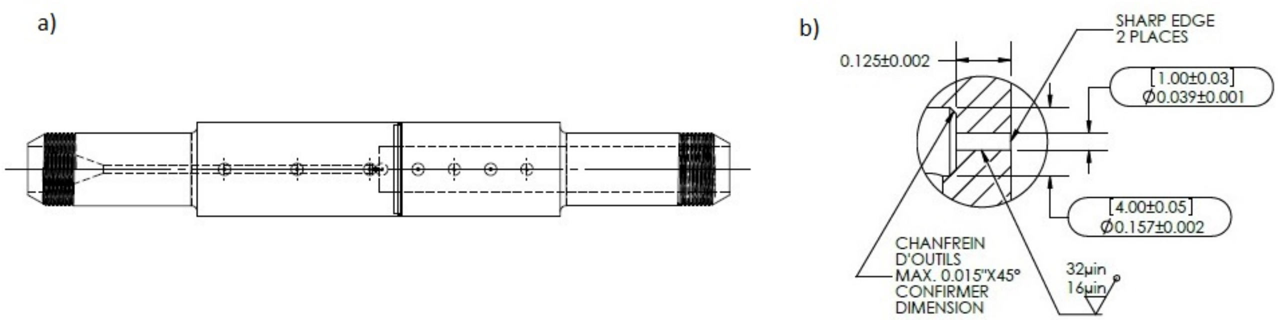

Figure 2. Test section with 1 *mm* orifice plate and pressure taps.

3. Experimental Conditions and Procedures

Experiments were performed for a wide range of flow pressures and temperatures; Table 1 summarizes the experimental matrix applied to collect the data presented in this paper. At supercritical pressures, we were able to cover a wide range of subcritical and supercritical flow temperatures. In particular, subcritical values can be very useful for designing flow valve and nuclear safety components.

Table 1. Experimental matrix.

Collected Data Points	Upstream Pressure (*MPa*)	Upstream Temperature (^oC)	Discharge Pressure (*MPa*)
107	22.0 – 22.7	52 – 323	0.1 – 3.6
35	22.8 – 23.9	52 – 388	0.1 – 3.0
48	24.0 – 26.0	52 – 434	0.1 – 3.0
20	26.1 – 31.0	354 – 457	0.7 – 3.0

As was mentioned in the previous section, the medium-pressure steam-water loop (not shown in Figure 1) serves as a low pressure-controlled reservoir in such a way that the discharge pressure can be changed at will, independently of the flow pressure developed upstream of the orifice. Therefore, most of the experiments were repeated by changing the discharge pressure while maintaining all flow parameters constant in the supercritical branch.

To avoid corrosion due to the eventual presence of Oxygen in the loop, after each experiment the loop is shut-down and filled with compressed nitrogen. Consequently, before starting the experiments, the medium-pressure loop is run for a period of two to three hours at a pressure of 0.6 *MPa*. At this set-point, a degassing valve opens to the atmosphere to release completely non-condensable gases and then the medium-pressure loop is controlled to a desired value. Afterward, the experiments are performed by increasing slowly the pressure upstream of the orifice. It is important to mention that the pressure in the calming chamber (Figure 1) is increased over the critical value before applying thermal power to the heater element; this methodology is necessary to avoid the occurrence of CHF. For a given fluid pressure, a gradual increase of the power applied to the heater element permits its temperature to be increased at will. The use of two loops, allows the discharge pressure to be varied in small steps and thus, check whether or not the flow is choked. Flow measurements permit us to establish the maximum allowable flow discharge which can be reached for a particular set of supercritical water conditions.

Flow conditions both upstream and downstream of the orifice are maintained constant for several seconds before collecting data. At subcritical temperature and supercritical pressure conditions, the pressure is controlled within a band of ±0.01 *MPa*. For supercritical flow temperatures and pressures the control of the loop is quite complex and cumbersome. These difficulties will be discussed later in the text. Instead, the discharge pressure is always controlled within a band of ±0.005 *MPa* for the entire range of subcritical and supercritical experimental conditions.

Each experiment is systematically repeated three times; each record contains 100 measurements at 100 *ms* per reading. Due to the complexity of performing this kind of experiments requires the participation of three qualified persons. One person controls the medium-pressure loop, a second one controls both the high-pressure loop and the data acquisition system, and a third person surveys the status of five video cameras. This system permits us to survey the access to the laboratory as well as the correct operation of key mechanical components of the loops. This safety installation is connected to its own computer that is able to record any event, automatically triggered by a moving detector algorithm. [11]

4. Experimental Results and Analysis

Up to now, 210 data points have been collected at supercritical pressure water flow conditions using the test section described in Section 2.1. As a common practice, the difference between the fluid temperatures with respect to the pseudo-critical value is used to treat the data. To this aim, it must be mentioned that a new relationship is proposed to estimate the pseudo-critical temperature, which is given as:

$$\begin{aligned} T_{pc} &= 3.719 \times P + 291.92 \quad 22.1 \le P < 26.0\ MPa \\ T_{pc} &= 3.306 \times P + 302.68 \quad 26.0 \le P < 31.1\ MPa \end{aligned} \tag{1}$$

This equation differs from a similar one proposed earlier by Lee & Swinnerton [12] and recently used Chen et al. [5,6] In fact, it is observed that their correlation does not satisfy the definition of the pseudo-critical temperature. [2] Figure 3 shows a comparison of results obtained with the equation given in the literature and Equation (1). It must be pointed out that after comparing several thermodynamic libraries, Equation (1) was validated with values determined using the NIST Standard Reference Database 23. [13]

Equation (1) is used to treat the data presented in Figure 4. These data were collected for flow pressures ranging from 22.1 *MPa* to 31.0 *MPa*, flow temperatures ranging from 50^{o}C to 456^{o}C and for discharge pressures from 0.1 *MPa* to 3.5 *MPa*. This figure shows the effect of both the upstream pressure and temperature on mass fluxes. In particular, for flow temperatures lower than pseudo-critical values, choking flow seems to occur within a very limited region. Close to the pseudo-critical temperature, our experiments provide data in a region where up to now, are very scarce. In fact the collection of data close to pseudo-critical conditions is not an easy task.

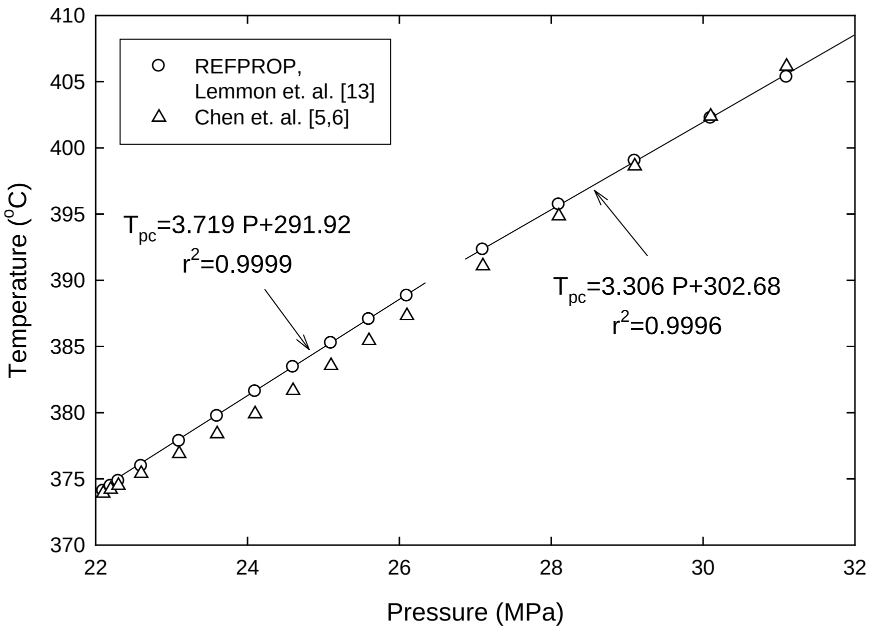

Figure 3. Comparison of results obtained with a new pseudo-temperature correlation.

Approaching the pseudo-critical point with $\Delta T_{pc} > 0$ the water heat capacity increases very rapidly while the mass density decreases, i.e., convective heat transfer increases fast even though the mass flow rate decreases. Consequently, when pseudo-critical conditions are reached, the difference between the inner surface temperature of the heater tube and the fluid temperature decreases very fast in a very noticeably way. This increase in heat transfer results in a quite fast increase in fluid temperature which triggers an unstable condition because the increase in temperature forces the density to decrease and the pressure to increase. In this region, the reduction in mass flow rate is not able to compensate the increase in pressure.

Over passing the pseudo-critical temperature ($\Delta T_{pc} < 0$), the heat capacity decreases quite fast, this in turn produces a decrease in heat transfer. Therefore, in this region, the critical mass flux continues to decrease while the temperature difference between the wall and the fluid increases which increases the fluid density and decreases the flow pressure. This situation makes the control of the desired fluid pressure to be very difficult. In parallel, for safety reasons, the maximum allowable surface temperature of Hastelloy C-276 tubing must also be respected along this process. Due to the extreme difficulty of controlling flow conditions close to the pseudo-critical point, measured fluid pressures and temperatures may shift by about 0.5% with respect to the desired values.

The experimental results presented in Figure 4 show that an increase in the fluid temperature results in a decrease in mass flux. Similar observations were also reported in the literature for both subcritical and supercritical water conditions. To this aim, Figure 5 shows a comparison of our experimental results with those given in.[4,5,12] The apparent discrepancy in the data can be explained by the difference in the geometry of the test sections used to perform the experiments. In fact, the same data are presented in terms of mass flow rates in Figure 6.

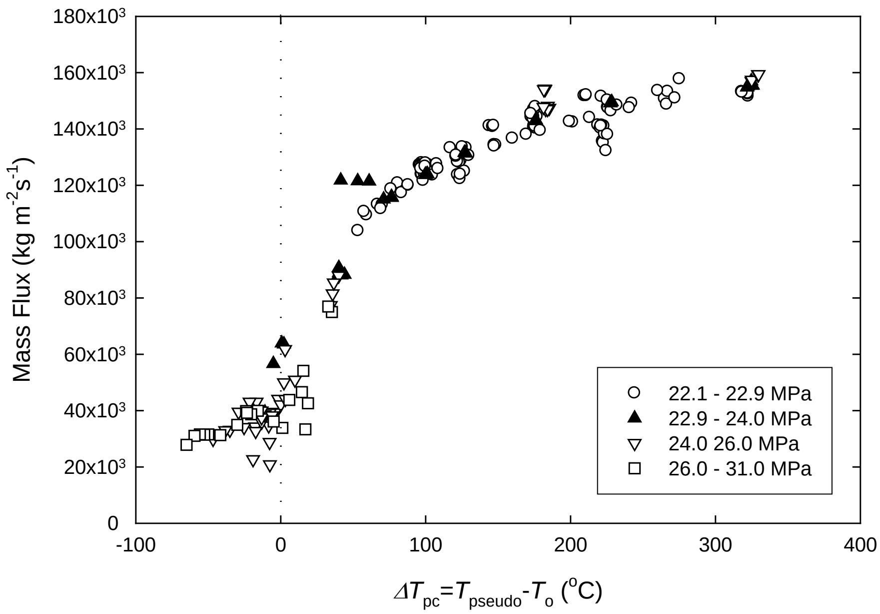

Figure 4. École Polytechnique supercritical water data.

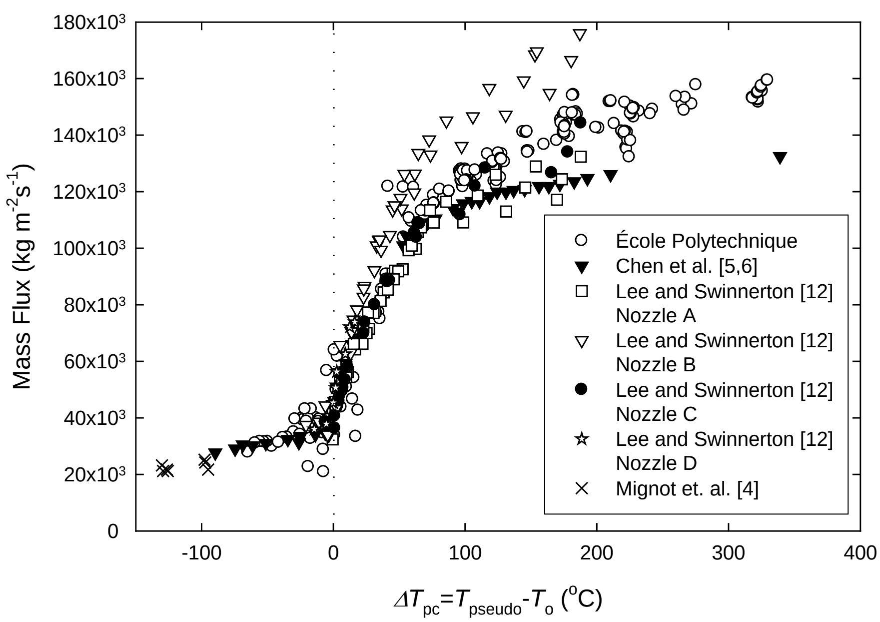

Figure 5. Comparison of École Polytechnique data with those given in the literature.

When the square ratio of orifice diameters is used (i.e., orifice cross-flow area ratios) there is a strong correlation between data collected by different researchers, with the exception of EPRI nozzle B. It must be pointed out that in this case the nozzle has round edges without baffle. [12]

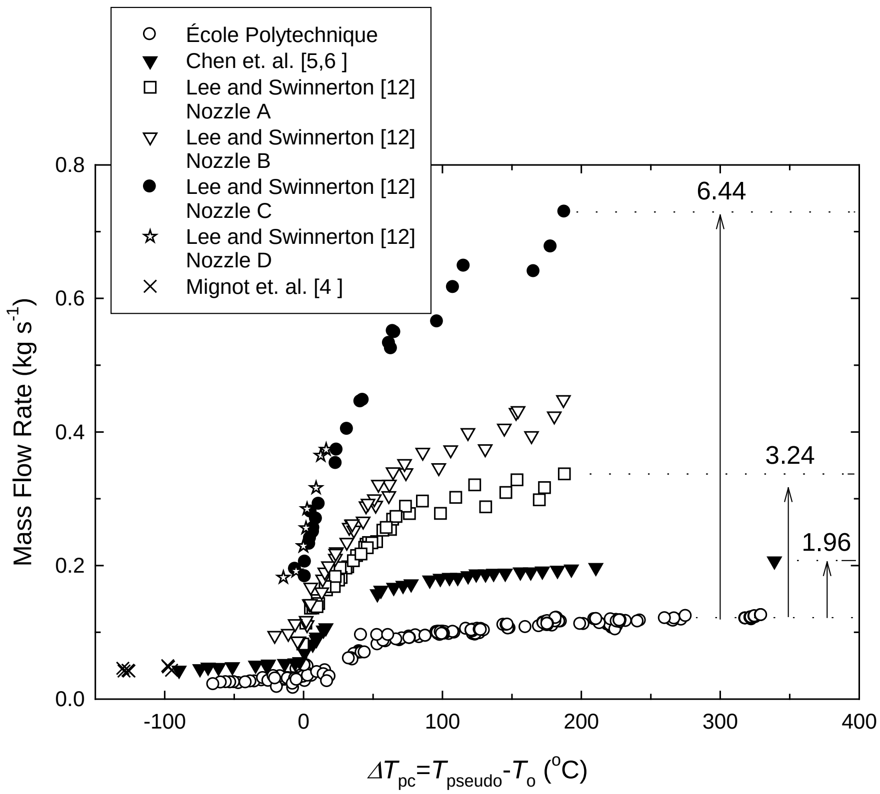

Figure 6. Effect of orifice diameter.

Since most experiments have been carried out at a single atmospheric discharge pressure, it is difficult to determine whether or not they satisfy choking conditions. In our case, the discharge takes place in a long 25.4 *mm* ID straight pipe under different discharge pressure conditions (see Table 1). Figure 7 shows the pressure distribution and the mass flux of a typical supercritical water experiment where the discharge pressure has been changed and carefully controlled. For each flow conditions more than three data values were collected at different time intervals; note that some of them appear superimposed in the figure. Upstream from the orifice Figure 7a shows a small pressure drop. Even though a dispersion of about +/- 0.4 *MPa* is observed in the data, the aforementioned reduction in pressure occurs systematically. Downstream of the orifice a systematic increase in the pressure profiles occurs. It is quite possible that these small changes are due to a partial recovery of the reversible component of the pressure drop in this region. In both cases, the behavior of the pressure upstream and downstream of the orifice necessitates more accurate measurements to be performed. To this aim, we are planning to change actual absolute pressure transducers by new differential ones and to modify the pressure measurement panel.

Figure 7b shows the mass flux obtained by maintaining upstream conditions almost constant and by increasing the discharge pressure from 0.7 to up to 3.0 *MPa*. It is apparent that increasing the discharge pressure does not affect the mass flux; thus, under the specified flow conditions choking flow is clearly achieved.

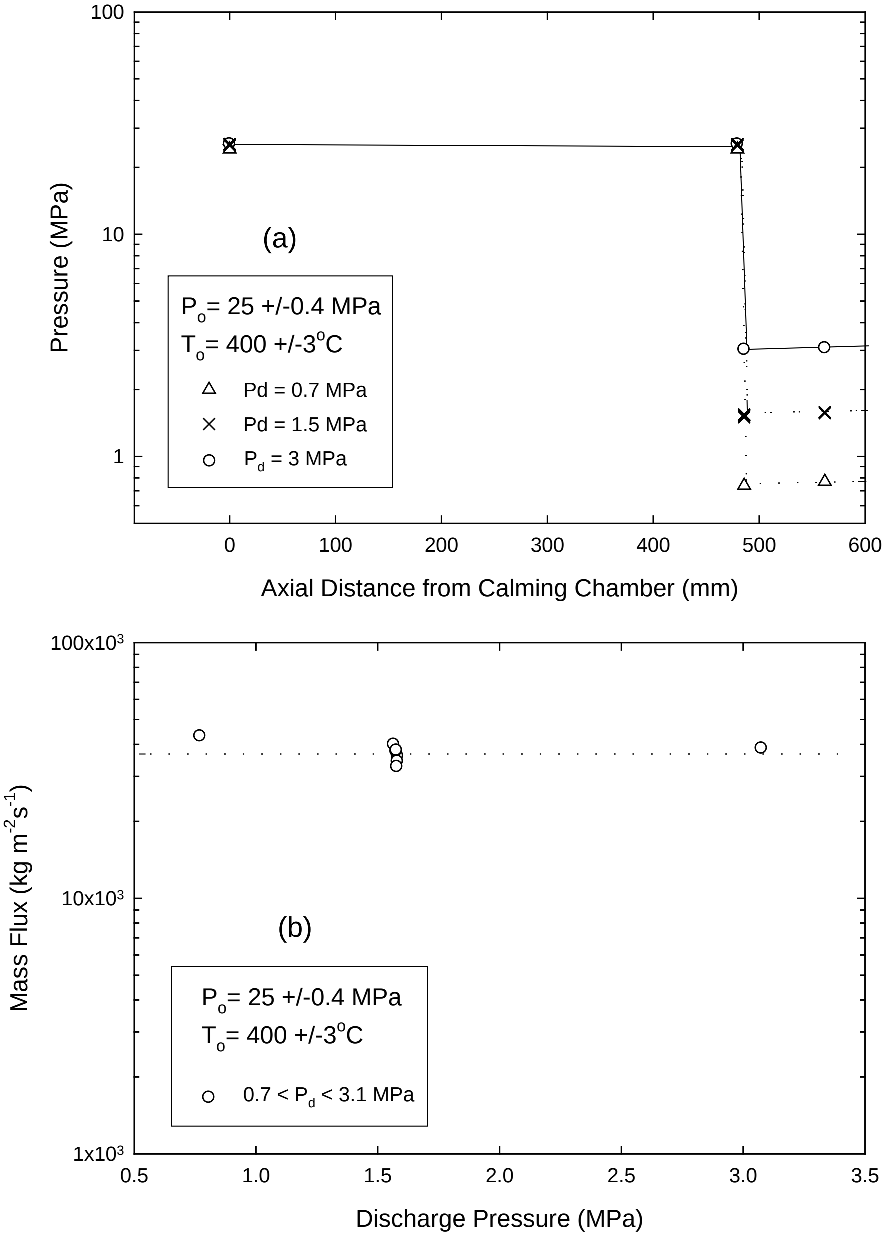

Figure 7. a) Pressure distribution along the test section vs. discharge pressure, b) Mass flux (Mass flow rate measured at 45 +/-2^o*C* and 25 +/-0.4 *MPa*).

Figure 7b also shows that the flow rate slightly decreases with increasing the discharge pressure. Careful data analyses indicate that the flow temperature at the inlet of the heater element was not completely steady. In fact, while the discharge pressure was increased from 0.7 *MPa* up to 3.0 *MPa*, the flow temperature changed from 43°*C* to 47°*C*. These results seem to indicate that the flow rate is sensitive to the flow temperature, i.e., fluid density.

5. Conclusion

Even though the boiler industry has more than 50 years of experience working with water at supercritical conditions, a review of the recent literature shows that the thermalhydraulics behavior of supercritical water is not completely known yet. In particular, experimental data is very scarce due to the complexity and the risks involved by these types of experiments. Therefore, most of the studies have been performed either using fluid different than water or far from operation conditions of SCWR's. To partially fulfill this lack of information, a supercritical water experimental facility has been constructed at École Polytechnique de Montréal.

The supercritical water set-up is used to perform choking flow experiments by covering a wide range of flow conditions. A test section having 1 *mm* diameter orifice with chamfered edges is used to collect the data presented in this paper. The results are compared with the study of Mignot et. al. [4], Chen et. al. [5,6], and Lee and Swinnerton. [12] In general, an excellent agreement with experiments carried out by other researchers is observed. In particular, the proposed experimental arrangement (i.e., use of two-loops running in parallel) permitted us to determine flow conditions that trigger supercritical water choking flow. Furthermore, a small pressure gradient occurring upstream of the orifice is systematically measured. We have also observed that close to the pseudo-critical point, the heat transfer coefficient changes very rapidly which affects the difference between the inner tube surface and coolant temperature. These fast variations combined with the corresponding change in fluid density, makes it very difficult to control and maintain flow conditions in the proximity of the critical point. Work is underway to modify the geometry of the test section and to implement more precise differential pressure measurements both upstream and downstream of the orifice.

Acknowledgements

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