

EXPERIMENTS AND ANALYSES OF SUPERCRITICAL CO₂ FLOW
INSTABILITY WITH STUDY OF DIMENSIONLESS PARAMETERS

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Abstract

Very limited experimental data on supercritical flow instability is present in the literature. To enrich this limited database and to further the understanding of supercritical flow instability, an experimental study was conducted using two vertical parallel channels facility (TVPC) with supercritical CO₂ flowing upward. A total of 23 experimental cases were performed on the new facility; sixteen were published by Saini (2019) and the rest of the cases are presented herein. The system pressure for the seven new cases was in the range 8.25 – 9.1MPa and the inlet temperature was in the range 0.5 – 10.05 °C. For all the cases, oscillatory flow instability was observed.

The current and the previous experiments performed by Saini were numerically analyzed without and with wall-heat storage effect using an in-house 1-D linear program. The numerical results showed good agreement with the experimental data. The inclusion of the wall-heat storage effect, for this parallel-channel system, yields a very small effect on the flow stability boundary. In addition, the dimensionless parameters proposed by Ambrosini and Sharabi (2008) for supercritical flow were examined using CO₂ experimental instability data in combination with the numerical results. The dimensionless parameters performed very well.

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Nomenclature

P_{cr}	Critical pressure
T_{cr}	Critical temperature
P_{pc}	Pseudo-critical pressure
T_{pc}	Pseudo-critical temperature
m	Mass flow rate
ρ	density
N_{spc}	sub-pseudo-critical number
N_{tpc}	true trans-pseudo-critical number
β	isobaric thermal expansion coefficient
C_p	constant pressure specific heat
h	specific enthalpy
P	electrical power
Q	Energy balance power
V	Voltage Drop
R	Electrical Resistance
ΔP_{total}	Total pressure drop
ΔP_f	frictional pressure-drop
ΔP_l	local pressure-drop
ΔP_g	gravitational pressure-drop
G	mass flux
ID	Inner diameter

OD	Outer diameter
g	gravity
H	Height of section
F_r	friction factor
Subscript	
Cr	Critical point
Pc	Pseudo-critical point
In	Inlet of channel
Out	Outlet of Channel
$exp.$	Experimental
Acronyms	
TVPC	Two vertical parallel channels
SCWR	Supercritical water reactor
SC	Supercritical
UM	University of Manitoba
EL	Electrical
EB	Energy Balance
LP	Linear program
WH	Wall-heat

Chapter 1 Introduction

1.1 Motivation

Fluid near its critical point is an efficient source of heat transfer due to the large specific-heat value and large coefficient of thermal expansion (Zuber,1966). Demand for higher system efficiency has generated interest in using supercritical flow as the working fluid. Many engineering systems like nuclear reactors, heat-exchangers, nuclear rocket engines, supercritical boilers and micro-channels used in electronic devices use the supercritical fluid as a working fluid. The use of supercritical fluids in engineering applications has made it necessary to better understand the limit of stable operation.

Many investigations done to improve the understanding of supercritical flow behavior reveal that at certain supercritical conditions, mass flow oscillations may occur. Mass flow oscillations are undesirable in general and can be detrimental to the efficient working of an engineering system. This is because of the mechanical vibrations and thermal fatigue that are caused by these oscillations. There is also the possibility of over-heating of the structure. In nuclear reactors, flow oscillations can induce divergent power oscillations and critical heat flux, which would be a safety issue. In nuclear rocket engines that use supercritical liquid propellant, these oscillations can induce combustion instabilities, which may result in system failure. Therefore, for the safe working of an engineering system, it is necessary to determine the conditions that initiate mass flow oscillations so the system can operate away from those unsteady conditions.

1.2 Supercritical Fluid

When the temperature and the pressure of the fluid is above its critical point, then the fluid is said to be in the supercritical region. In this region, the distinction between the liquid and gas phases disappears, and fluid is in a single homogenous state having unique properties of both liquid and gases. The main supercritical fluids used are water and CO_2 .

Critical Point – It is a point where the distinction between the liquid and gas phases becomes indistinguishable from one another. The critical point is the end of phase equilibrium curve. It is defined by critical pressure P_{cr} and critical temperature T_{cr} . At this point, there is no phase boundary.

Pseudo-Critical Point – It is a point having pressure above the critical pressure and temperature corresponding to the maximum value of the specific heat at each supercritical pressure. The P_{pc} and T_{pc} characterize it. Figures 1.1 and 1.2 show the phase diagram.

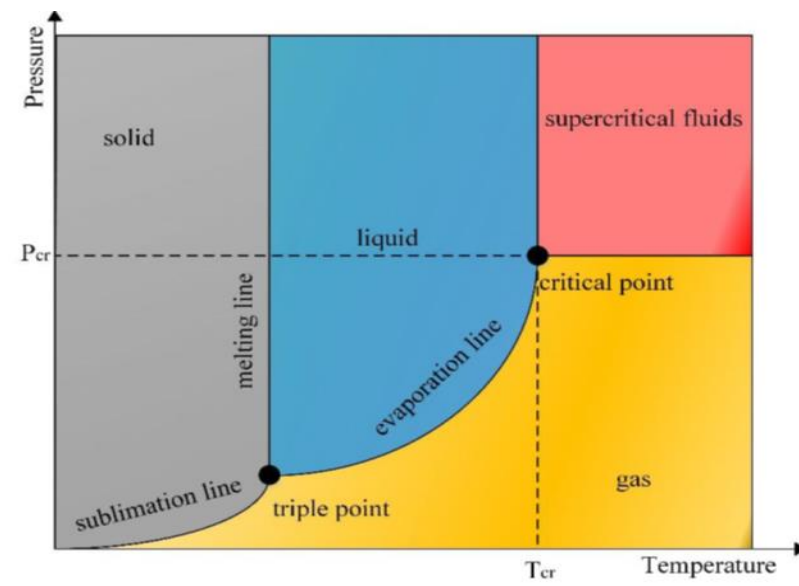


Figure 1.1: General Phase diagram.

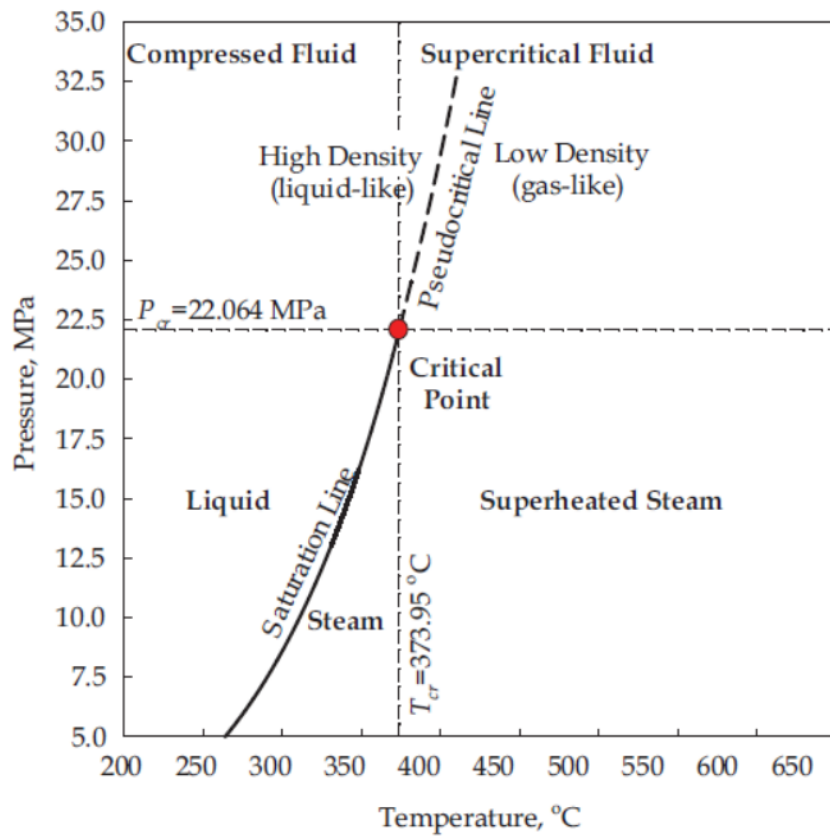


Figure 1.2: Phase diagram of water showing critical and pseudocritical points.

1.3 General Concept of Stable/Unstable flow System

The system flow is said to be stable when any small perturbation applied to its steady-state (in terms of any parameters like velocity, density, pressure, power) damps out to produce its original steady-state. However, if due to applied perturbation the flow attains a new steady-state, or the oscillations continue to grow in amplitude, then the system is unstable. The system flow is neutrally stable if it keeps oscillating with the same amplitude. Generally, at instability boundary, flow oscillations usually form a repetition pattern and can be periodic or chaotic (Shitsi et al.

2018a). Most researchers have recommended that the amplitude value for the unstable system should be at least $\pm 10\%$ of the steady-state value (Shitsi et al. 2018a).

1.4 Types of Supercritical Flow Instability

Generally, two types of flow instability at supercritical conditions have been reported so far.

1. Static flow instability/ Ledinegg Instability.
2. Dynamic flow instability/Oscillatory flow instability.

1.4.1 Static flow instability /Ledinegg Instability

In the static or Ledinegg instability, the mass flow rate changes its original steady-state to a new steady-state or diverges.

1.4.2 Dynamic flow instability/ Oscillatory flow instability

In the dynamic flow instability, the mass flow rate in the channel starts oscillating in a diverging manner. In a two-channel flow, the flow rate oscillates 180° out-of-phase.

1.5 Outline of thesis

Chapter 1 introduces the motivation for the present research work, some general terminology, flow instability concept and its types, and outline of the thesis.

Chapter 2 reviews the works on supercritical flow instability for single and parallel channels. The research objective and a summary of the literature work are also presented.

Chapter 3 discusses the experimental facility used for flow stability analysis. Details about the test section facility, components and instruments, and test procedures required to find the flow instability are discussed.

Chapter 4 presents the experimental results of the conducted experiments. A total of seven experiments were performed. Details like the instability boundary analysis, flow behavior in channels, temperature oscillations, energy balance power vs. electrical power, oscillation period, fluid transit time, uncertainty in instability boundary, and expression of experimental data in dimensionless form are discussed.

Chapter 5 presents the performance of the 1-D linear program to model the supercritical CO₂ experimental data. It also presents the results obtained from the assessment of dimensionless parameters proposed by Ambrosini and Sharabi (2008).

Chapter 6 summarizes the summary, conclusions, findings and recommendations drawn from the current research work.

Note: There will be frequent occasions throughout in subsequent chapters when we will come across terminology “instability boundary or stability boundary”. However, these terms are not separate terms. They represent similar meanings i.e. the mass flow rate when it just began to oscillate.

Chapter 2 Literature Review

2.1 Introduction

Flow instability is highly undesirable in most engineering systems as it can limit the performance of the system, can affect the system safety, and can cause material fatigue. The study of flow stability started in the nineteenth century, most notably by Helmholtz, Kelvin, Rayleigh and Reynold. They provided many useful tools for the flow stability study. As time proceeded, the investigating process for flow stability analysis also evolved. The early theoretical work to examine flow stability begins with the linear perturbation theory and frequency domain. However, with the advancement of the computer systems, the time-domain solution evolved. Nowadays, the CFD is gaining popularity. In addition, very few numbers of experiments have been performed because of the high construction and operating costs required for high pressure and high temperature. Described below are the approaches mainly adopted by researchers to study flow stability.

1. Frequency Domain Solution

The Frequency Domain approach deals with linear systems only and the concept relies on control theory. The steady-state solution is required prior to finding the frequency domain solution. Once, the steady-state solution is obtained, the governing time-domain equations (mass, momentum, and energy) are linearized by applying a small perturbation about the steady state. After that, the equations are converted to frequency-domain by applying the Laplace transform, and the transfer function is derived. The stability of the system can be easily determined from the Nyquist plot and/or Bode plot. The solution to this method is exact in time and is less time-

consuming. However, it ignores the effect of non-linear terms and does not predict the limit cycle or amplitude of the oscillations.

2. Time Domain Solution

The Time Domain solution uses the governing equations of mass, momentum, and energy, which are discretized in space and time by using some form of discretizing methods like finite difference or finite volume method. The solution to the steady state is obtained first. This steady-state solution is used as an initial condition for the transient analysis. A perturbation is applied to any parameter. If due to the applied perturbation, the flow oscillations decay with time, the system is stable. If it grows with time, then the system is unstable, and if it remains constant, then the system is neutrally stable. The solution to this method includes all non-linear terms and the flow characteristics, like amplitude and cycle of oscillations, can be determined. However, the solution is not exact in time, is more time consuming, and is susceptible to numerical instabilities.

3. Experiments

Experiments capture the real-time response of the flow and includes all external effects. The data obtained from experiments would be valuable for validating the above numerical approaches. However, very few experiments have been performed because of high construction costs, high operation costs and high working conditions.

Plenty of research on sub-critical flow instability is available in the open literature. However, research on supercritical flow instability is still developing; therefore, only a limited amount of literature (especially for parallel channels) is available. The flow instability in parallel channels has received considerable importance in the past because engineering systems like Super-critical

water reactor (SCWR) comprises many parallel channels connecting the inlet and outlet headers. Any flow oscillations in the parallel channels connecting the inlet and outlet headers are deemed highly undesirable. Because it can induce divergent power oscillations and critical heat flux which are a limit for stable operation. Hence, it is necessary to acquire a better understanding of flow behavior in parallel channels.

Though, the numerical analysis of a single channel is considered as a good option to save computational time, it is nearly impossible to perform single channel experiments without having a bypass channel; however, two parallel channels can be studied experimentally. In this chapter, the relevant works performed on single and parallel channel supercritical flow instability are discussed. The works discussed fall in two sections, which are:

1. Numerical work
2. Experimental work

2.2 Numerical work on Supercritical flow instability

Zuber (1966) performed early theoretical work on supercritical flow instability for a single channel. The governing equations were linearized by applying a small perturbation to the inlet flow and linear equations were integrated over the channel length to obtain the characteristic equation. The study confirmed that the parameters that promote and prevent the flow instability at supercritical conditions were, in fact, the same as for boiling system.

D'Auria et al. (1993) analyzed the occurrence of flow instability in the new generation reactors. The finding was that the flow instability largely depends upon the local loss coefficients.

Yi et al. (2004) examined the flow instability in supercritical pressure-light water reactor using an in-house 1-D linearized program in the frequency domain. The results were that the flow stability increases with a decrease in the channel inlet temperature, increasing inlet pressure-drop coefficient and by decreasing power to flow ratio. They concluded that achieving a suitable inlet pressure drop coefficient will make the reactor to operate stably.

Zhao et al. (2005) created a stability map for the operation of the U.S reference SCWR design by examining flow instability in a single vertical channel. A three-region model for supercritical flow was proposed. The governing equations were reduced to dimensionless form, and linear perturbation theory in the frequency domain was applied to study the stability of the flow. The stability map for the operation of the U.S reference SCWR design was constructed using dimensionless numbers. The study confirmed that the flow stability of the system increases with an increase in the channel inlet pressure drop coefficient.

A 1-D linear in-house program for a single-channel flow was developed by Chatoorgoon and Upadhye (2005). The purpose of the study was to verify the previous predictions obtained from a 1-D non-linear in-house program, SPORTS (Chatoorgoon,1986). The results of the two programs proved to agree very well within 95% accuracy. They concluded that the non-linear (SPORTS) results were not the artifact of numerical instabilities. Later, Chatoorgoon and Ghadge, (2018), extended this linear program to two parallel channels, including the wall-heat storage effect. This linear program was used in the present study to analyze the CO₂ experiments.

Amborsini (2007) drew an analogy between sub-critical flow instability and supercritical flow instability. A uniformly heated channel was modeled using RELAP5 under both conditions. The obtained results clearly showed that oscillatory and static instability can occur in both subcritical

and supercritical systems. Low inlet temperatures were favored for the occurrence of static instability at supercritical conditions. The study also reported that instability phenomena occurring at subcritical and supercritical conditions are governed by the same principles.

The dimensionless parameters, N_{tpc} and N_{spc} , were proposed by Ambrosini and Sharabi (2008) for supercritical flow. Initially, they were assessed for water, but later Ambrosini (2011) assessed them for CO₂, Ammonia, and R23 also. These parameters proved to perform very well for all fluids for flow stability analyses. These parameters are very useful for scaling purposes and can be applied to stability boundary analyses; however, they were limited to the same geometry with the same set of K -factors and work only up to certain range of N_{spc} .

Chatoorgoon (2008) and Chatoorgoon (2013) examined oscillatory and static flow instability in two identical parallel channel system. This study pioneered the research in parallel channels. Dimensional parameters were produced and assessed for the stability boundary analyses. These parameters were specific to the supercritical parallel channels; however, were considered as the simplest way of assessing flow stability analyses in heated channels with just requiring a steady-state solution of the system. Thus, saving the transient analyses time. The dimensionless parameters proved to be a good engineering tool for stability boundary analyses. The results revealed that the vertical down-flow is most susceptible to static instability, as compared to vertical up-flow and horizontal flow. The static instability is least likely to exhibit in vertical up-flow orientation.

Sharabi et al. (2008) made the first attempt using the commercial CFD software, FLUENT, for the analyses of supercritical flow instability in a single heated channel. The addressed geometry was like that used by Ambrosini (2007, 2008). The CFD models predicted the onset of unstable

behavior in a single heated duct, and predicted results close to the 1-D models. The oscillation period predicted by the standard k-e model with wall functions was similar to that predicted by the 1-D system code, RELAP5. Further, the FLUENT code predicted the correct effect of the inlet and outlet pressure drop on the flow stability.

Sharabi et al. (2009) extended the CFD FLUENT work for the stability analyses of SCWR rod bundle sub-channels. The inlet and outlet valve throttling were neglected. The results revealed that the characteristics of density wave oscillations in triangular and square pitch assemblies were similar to circular channels.

Yeylaghi et al. (2011) assessed the dimensionless parameters proposed by Chatoorgoon for static flow instability in supercritical down-flow channels. Chatoorgoon's method naturally filtered out those cases that were not a static instability and they found that Chatoorgoon dimensionless parameters correlated well with numerically predicted instability data. They found that vertical down-flow was the most unstable orientation compared to horizontal or vertical up-flow. Increasing inlet K-factor stabilizes the system flow, whereas increasing outlet K-factors destabilizes the system flow. In most of down-flow cases, they found that channel outlet temperature was close to pseudo-critical point.

Xiong et al. (2013) analyzed the experimental data they performed. A 1-D non-linear program was developed, and the original experimental geometry was simplified and studied. They reported that the results were in good agreement with the experiment data. Further, there exists an inflection point for the channel inlet temperature increase. Below the inflection point, the flow stability decreases with the channel inlet temperature increase. Above the infection point, the flow stability increases with the channel inlet temperature increase.

Su et al. (2012) examined the flow instability in two vertical parallel channels using supercritical water. A 1-D non-linear program (TIMDO) was developed. They explained that the flow instability in two vertical parallel channels occurs when any disturbance to mass flow is not absorbed by the interaction of pressure drop and distribution of mass flow in the channels. Consequently, the mass flow becomes unstable and starts oscillating 180° out-of-phase. The results revealed that the flow stability increases with decreasing the diameter of the heated section, increasing system pressure, and increasing frictional pressure drop.

Ampomah-Amoako et al. carried out a series of flow instability studies in a 3-D nuclear reactor sub-channels and a 1-D heated channel using the 3-D CFD software, STAR-CCM+, and 1-D code, RELAP5 (Ampomah-Amoako et al., 2013; Ampomah-Amoako and Ambrosini, 2013). They gave an insight into the development of the CFD methodology and confirmed the capability of the CFD code to predict unstable flow behavior. Vertical up-flow, vertical down-flow, and horizontal flow were all studied using STAR-CCM+, and RELAP5. They reported very good agreement. They suggested that the flow instability phenomena were mainly characterized by 1-D flow behavior.

Debrah et al. (2013a) used a 1-D non-linear program to examine the effect of wall-heat storage on the flow stability boundary of a natural circulation loop. They reported that the system becomes significantly more stable when the wall-heat storage was modeled. The results without wall-heat storage were closer to the experimental data compared to with wall-heat storage. Further study with different heat transfer correlations was also suggested. In addition, they also examined the effect of three reduced thermal capacitances of wall on the flow instability

boundary (Debrah et al., 2013b). They concluded that for numerical flow stability analyses, the wall-heat storage effect should be omitted.

Xi et al. (2014a) modeled Xiong et al. (2012) experiments using CFD software, ANSYS-CFX. They compared their numerical results with the 1-D numerical results of Xiong et al. (2013) and their experiment data. The CFD results were closer to the experimental data compared to the 1-D numerical results. However, the CFD analyses showed a discrepancy in predicting the oscillation period. The CFD code predicted the oscillation period of 4.5 sec., whereas the experimental oscillation period was 1 sec. Moreover, in the experiments, the mass flow oscillations were of fixed amplitude, but in the CFD analyses, mass flow oscillations were diverging. They reported that the effect of system parameters such as system pressure, gravity, and inlet mass flow rate on the commencement of flow instability in CFD results was different from that obtained by 1-D code. Especially the gravity effect, which not only affected the instability power, but also the oscillation period.

To verify the predictions made by Xi et al. (2014a), the CFD analyses using ANSYS-CFX was carried out by Li et al. (2018), modeling Xiong et al. (2012) experiments. The results obtained were compared with the experiment data and the 1-D non-linear results predicted by Chatoorgoon SPORTS code (Chatoorgoon,1986). They reported that the 1-D analyses better predict the flow stability boundary than the 3-D analyses. This finding contradicted the previous finding of Xi et al. (2014a). The reason cited was the different time step-size in the CFD studies. Also, the different boundary conditions imposed at the inlet and the outlet of channels in 1-D analyses. Li et al. (2018) used a smaller time step size compared to Xi et al. (2014a). In 1-D SPORTS code simulation, the stagnation pressure boundary condition was imposed, whereas

Xiong et al. (2013) imposed a static pressure boundary condition at the inlet and the outlet of the channels. These yielded different results. The CFD analyses did not predict the oscillation period correctly. It predicted an oscillation period of nearly 5 seconds, whereas the experimental oscillation period was 1 second. They also reported that increasing the outlet K -factor of the hotter channel will make the flow more unstable than increasing the outlet K -factor of the less-hot channel. The use of a first-order transient scheme in CFX was recommended for future studies, as the transient response of the second-order transient scheme was not smooth. The second order scheme took a much longer time to capture identifiable oscillation patterns. However, later, Ghadge (2018) found that the unsmooth curves were basically hidden frequencies.

Following Li et al. (2018) work, Ghadge (2018) analyzed Xiong et al. (2012) and Xi et al. (2014b) experiments using a 1-D in-house linear program and the CFD software, ANSYS-CFX. Ghadge reported a similar finding with Li et al. (2018) but contrary to Xi et al. (2014a). The 1-D linear results were closer to the experimental data compared to the CFD results. Ghadge concluded that frequency domain solution predicts the flow instability boundary better than the time domain solution. Ghadge advised using the second-order transient scheme, full geometry and smaller time-step in the CFD modeling for improving the instability boundary and oscillation period predictions. Ghadge reported that modeling the wall-heat storage yielded more accurate predictions, especially of the oscillation period. Also, Ghadge was the first to apply the Fast Fourier Transformation on experimental and CFD results for the prediction of the oscillation period. Various hidden oscillation periods were revealed. The less dominant oscillation period of 5 seconds was reported for Xiong et al. (2012) experiments. This explains the previous predictions of the oscillation period of 5 seconds predicted by various non-linear studies.

Li et al. (2014) examined supercritical flow instability in a single and two parallel vertical up-flow channels using the APROS simulation software. The obtained results were compared with the previous study results of Sharabi et al. (2008) and Xiong et al. (2012). The predicted and previous study results agreed well with an error between 3-8%. However, the software predicted the oscillation period incorrectly. For Xiong et al. cases, the software predicted an oscillation period of about 4 seconds, whereas the actual oscillation period was 1 second. The effect of the channel inlet temperature and the time step on the flow stability boundary was also examined. They showed that there exists an inflection point below which the flow stability of the system decreases with channel inlet temperature increase. And, above the inflection point, the flow stability of the system increases with channel inlet temperature increase.

Dutta et al. (2015) investigated the in-phase and the out-of-phase mass flow oscillations in a CANDU supercritical water reactor without considering the influence of the neutronic reactivity feedback. Multiple channels were modeled using a 1-D non-linear in-house program, THRUST. THRUST in-phase model was validated against the previous results of Dutta et al. (2014) and THRUST out-of-phase model was validated against the experimental results of Xiong et al. (2012). The numerical results were within 5% error of the experimental data. The results were presented on a 2-D plane using dimensionless numbers. They found that the out-of-phase mode had a smaller stable zone compared to the in-phase mode. The flow stability increased with an increase in the channel inlet pressure-drop coefficient for both oscillation modes. The flow became less stable as the asymmetry power between the channels increased, for both the in-phase and out-of-phase modes.

Sharma et al. (2015) examined the effect of the wall-heat storage on the flow stability boundary using a 1-D non-linear in-house program, NOLSTA-p. The program was validated against the experimental data of Xiong et al. (2012) with a maximum error of 8%. The study concluded that with the wall-heat storage effect, the flow stability boundary increased significantly for a natural circulation loop.

Ebrahimnia et al. (2016) studied the static and the oscillatory flow instability in a single vertical up-flow channel using the CFD software, ANSYS-CFX. The obtained results were compared with the SPORTS 1-D non-linear results (Chatoorgoon,1986). The predicted results were within $\pm 6.82\%$ error of the 1-D non-linear results. The obtained results were also compared with the approximate instability boundary criteria proposed by Ledinegg and Chatoorgoon.

The static instability results, when compared with the instability boundary criteria of Ledinegg and Chatoorgoon, showed that the predicted results were in better agreement with the instability boundary criteria of Ledinegg. For oscillatory instability cases, the results when compared to the criteria of Chatoorgoon, there was good agreement. They found that there is no significant effect on the flow stability boundary if either the k- ϵ turbulence model or SST turbulence model was used in the CFD modeling. The effect of changing the turbulent Prandtl number on the flow stability boundary had a negligible effect.

Shitsi et al. (2018b) simulated Xi et al. (2014b) experiments using the CFD software, STAR-CCM+. The numerical results were within 10% of the experimental data. The study reported that the change in system parameters had a very little effect on the oscillation period, but a significant effect on the amplitude of the mass flow oscillations. The amplitude of mass flow oscillations

increased with the lower system pressure, mass flow rate, and gravity effect compared to high system pressure, mass flow rate, and no gravity effect.

The effect of the wall-heat storage on the flow stability of a single vertical up-flow channel was examined by Liu et al. (2018). The developed 1-D non-linear program was validated against available data. They reported that when including the wall-heat storage effect, the flow stability boundary increases with increase in wall thickness. The effect of pipe length on the flow stability boundary was also examined. They reported that a critical length exists for a pipe, below which the flow stability decreases with pipe length. Above the critical length, the flow stability remains constant with no wall-heat storage effect and increases with wall-heat storage effect. They also reported that increasing the wall thickness, the amplitude of the oscillation decreases, and the oscillation period increases.

Ghadge et al. examined the effect of the wall-heat storage on flow stability boundary for two vertical parallel channels (Ghadge, 2018.; Ghadge et al., 2020). Xiong et al. (2012) and Xi et al. (2014b) experiments were modeled using a 1-D linear program. They reported that modeling the wall-heat storage effect improved the prediction of threshold power and the oscillation period. The RMS error for Xiong et al. (2012) cases without and with wall-heat storage was 3.68% and 1.75%, respectively. For the Xi et al. (2014b) cases, the RMS error without and with wall-heat storage was 1.96% and 1.60%, respectively. They reported that the inclusion of the wall-heat storage has a large stabilizing effect on flow stability boundary for a single vertical up-flow channel. However, there is a small stabilizing effect for two slightly different vertical parallel up flow channels and zero effect for two identical vertical parallel channels. The effect of wall-heat storage perfectly cancels out between the channels when modeling two identical parallel

channels. They also showed that instability threshold power increases up to certain limit with increase in wall-thickness. Thereafter, it remains constant. This was the first reported study to report good agreement with the experiment using the wall-heat storage effect.

Saini (2019) used data from 30 experimental cases to assess the licensing CATHENA code v.3.5.4.4 (Beuthe et al.,2014) performance on supercritical flow instability in two vertical up-flow parallel channels. 14 experiments were with water, out of which 9 experiments were performed by Xiong et al. (2012) and 5 by Xi et al. (2014b). The remaining 16 experiments were with CO₂ performed by Saini himself. Since the version of CATHENA could model only water, the experimental data of CO₂ were converted into H₂O data using Ambrosini and Sharabi (2008) dimensionless parameters. This was the first attempt to use CATHENA (v.3.5.4.4) with data converted from CO₂ to H₂O. Saini reported that for the 30 cases simulated, 5 cases did not converge to yield an initial steady-state solution. 3 non-converged cases were of Xiong et al. (2012) and the remaining 2 were of Xi et al. (2014b) and Saini (2019). The numerical and experimental results for the remaining cases of Xiong et al. agreed with an error between 3.78–7.23% and with an RMS error of 6.05%. For Xi et al. cases, the error was between 12.45–15.29% with an RMS error 13.84%. For Saini’s cases, 7 cases showed a reasonable agreement error between 0.22–6.81%, and another 8 cases showed agreement error between 9.66–25.68%. Saini concluded that CATHENA was able to predict reasonable results for nearly half of the cases; for the rest of the cases the error was large.

Saini also reported the inability of the CATHENA code to predict the correct oscillation period. The same oscillation period of 3.3 sec. was found for all cases, whereas the experimental oscillation period varied from case to case. Therefore, Saini concluded that the CATHENA code

does not predict an accurate oscillation period for a parallel channel system. Saini also studied the effect of wall-heat storage on the two parallel channel up-flow instability boundary using CATHENA. Three different wall thicknesses, 0.01, 0.1 and 0.5 mm were used to check the sensitivity of the wall thickness on the instability boundary. Saini concluded that with the thickness of 0.01mm, CATHENA prediction was close to the no-wall solution; however, when wall thickness was increased to 0.1mm, CATHENA yielded unrealistic results with an error of 29.45% compared to the no-wall thickness. For 0.5mm, the result had an error of 82.53% compared to the no-wall result. Saini concluded that CATHENA (v.3.5.4.4) was unable to predict realistic results with wall-heat storage.

The comparison of CATHENA v.3.5.4.4 (Beuthe et al.,2014) results with the 1-D linear results of Ghadge et al. (2020) showed that the 1-D linear program did a much better job of predicting supercritical flow instability in parallel channels than the non-linear CATHENA v.3.5.4.4 code.

2.3 Experimental work on Supercritical flow instability

Relative to the numerical work, the experimental work performed on supercritical flow instability is insufficient and sparse. Below discusses the experimental work performed on parallel channel supercritical flow instability.

Xiong et al. (2012) reported instability experiment data with two vertical parallel channels using supercritical water flowing upward. The test section consisted of two vertical parallel channels made up of INCONEL alloy pipes having inner and outer diameter 6 and 11 mm, and length 3000 mm. Nine instability experiments were performed. The channel mass flow rate distribution with input power increase was examined. The results showed that at a low heating power, the mass flow rate was almost symmetric in the channels. With an increase in heating power, it

distributed unequally between the channels. With further increase in heating power, irregular oscillations started, and near the flow instability boundary, the channel inlet flow rate oscillated 180° out-of-phase. A parametric study was also performed. The researchers confirmed that an increase in system pressure stabilizes the system. However, an increase in the channel inlet temperature destabilizes the system. The point of inflection for temperature was not reached because of the temperature limit of the experimental facility. The study provided valuable instability data for code validation purposes.

Xi et al. (2014b) performed experiments on the same experimental facility used by Xiong et al. (2012), but with a thicker pipe wall. The channels were replaced with two other INCONEL 625 pipes of inner and outer diameters 6 mm and 19 mm, respectively, and length of 3105 mm. Each pipe was divided into two sections by using three copper plates arranged in an axial direction. The section close to the inlet of channels was called the inlet section and the section close to the outlet of channels was called the outlet section. Five uniform and seven non-uniform power profile instability experiments were performed.

The aim of these experiments was to study the effect of the non-uniform power profiles on the flow stability boundary. However, the non-uniform power profile cases were unrealistically large step for a nuclear reactor, as in nuclear reactor the power variation is gradual.

Three kinds of axial power profiles were studied: axially increased, uniform, and axially decreased. For the axially decreased power shape, the power applied to the inlet section was held constant and the power to the outlet section was increased in steps with time. For the axially increased power shape, the power applied to the outlet section was held constant and power to the inlet section was increased in steps with time. For the uniform power shape, the axial channel

power was uniform and incremented that way. They found that for the axially decreased power shape, the flow instability boundary occurred twice. The first one occurred when the channel outlet temperature was close to the pseudo-critical point and the oscillation period was 1.6 sec. The second one occurred when the channel outlet temperature exceeded 500 °C and the oscillation period was 1.3 sec. No flow instability was observed for the axially increased power shape within the operating limits of the experimental facility. They reported that the axially increased power shape was the most stable power shape followed by the uniform and axially decreased power shape.

Saini et al. (2020) performed instability experiments with two vertical parallel channels using supercritical CO₂ flowing upwards. This was the first reported study for parallel channels using supercritical CO₂. Eleven instability experiments were reported. The test section consists of the two vertical channels made up of INCONEL 825 having inner and outer diameters 16.56 mm and 19.05 mm respectively, and of length 1500 mm. Experiments were performed with a wide range of system parameters. The results were used to assess the CATHENA code. The same experimental facility was used in the current study.

2.4 Research Objective

As apparent from the literature, the experimental work performed for parallel channel supercritical flow instability is sparse. Therefore, the main objective of this study includes performing new parallel channel flow instability experiments using the same facility used by Saini (2019), but with lower inlet temperatures in search of static instability. Saini (2019) performed experiments at higher inlet temperatures. Providing experimental data with a wider range will be useful for furthering the understanding of flow instability and provide useful data for validating existing or

new software. Validating a methodology against a wide range of experimental results makes the methodology reliable for engineering use and provides useful information about the suitable numerical methodology to be used for flow stability studies. The other objectives of the study include:

- a) Assess an in-house 1-D linear program's ability to model the flow instability boundary with supercritical CO₂ in a parallel-channel configuration, as previously it was only done for water. Validating the program for multiple fluids over a large number of experimental databases would provide useful information about the suitable numerical methodology for flow stability studies. This can help further the understanding of SC flow instability in various geometries and configurations without necessarily performing expensive experiments. The numerical methodology information would also be useful to other researchers who wish to develop new computer programs for flow stability studies.
- b) Numerically study the effect of wall-heat storage on the instability boundary as most previous studies for two parallel channels were without wall-heat storage effect. Knowing the effect of wall-heat storage on the instability boundary will yield recommendations for future studies.
- c) Compare the oscillation period without and with wall-heat storage. Wall-heat storage would affect the oscillation period and an accurate numerical model should capture this change.
- d) Assess Ambrosini and Sharabi dimensionless parameters to accurately convert instability CO₂ data to H₂O instability data. This assessment is important because engineering systems, like nuclear reactors, would invariably use supercritical water as the working

fluid and accurate water data is more relevant. For safety and economic reasons, it is favored to perform experiments with fluids that have a lower critical pressure and temperature, like CO₂. Verifying Ambrosini and Sharabi's dimensionless parameters work well for transforming instability data of CO₂ to H₂O would make it a very useful engineering tool.

2.5 Summary of Literature Work

Table 2.1 summarizes the numerical literature work done on channel supercritical flow instability and Table 2.2 summarizes the experimental literature work done on channel supercritical flow instability. The work related to two-phase flow instability and loop instability is omitted here as present research only deals with the two parallel channel flow instability at supercritical conditions. From Table 2.2, it is evident that the experimental work for channel supercritical flow instability is very limited compared to the numerical work, and it was the one of the main reasons to perform experiments in present research work.

Table 2.1: Numerical summary of channel supercritical flow instability.

Reference	Study Description	Findings and comments
Yi et al. (2004)	Parametric effects on supercritical flow stability boundary for a single vertical channel. Code: A 1-D linear in-house program. Fluid: Water.	1) The flow stability of system increases with decreasing the inlet temperature, increasing inlet pressure drop coefficient and decreasing power to flow ratio. This is well known for two-phase flow instabilities, concluding the mechanism of two-phase flow instabilities and supercritical flow instability is alike.
Zaho et al. (2005)	Numerical study of supercritical flow instability in a single vertical channel. Code: A 1-D linear in-house program. Fluid: Water.	1) Developed the stability map for the operation of the U.S reference SCWR design. 2) Increasing the channel inlet pressure drop coefficient increases the flow stability

		boundary.
Chatoorgoon & Upadhye (2005)	Development of the linear program for a single-channel flow for stability analysis. Code: A 1-D linear in-house program. Fluid: Any Fluid	1) The 1-D linear and non-linear results agreed well within 95% accuracy.
Ambrosini et al. (2007)	Analogy of instability analysis under sub-critical and supercritical flow conditions. Code: RELAP5, Linearized program. Fluid: Water.	1) Oscillatory and static instability occurs under both sub-critical and supercritical conditions. 2) Low temperatures are the favourable conditions for static flow instability.
Ambrosini et al. (2008,2011)	Deriving the dimensionless parameters for supercritical flow. Code: RELAP5, Linearized program, TRANSDIM Fluid: Water, Ammonia, CO ₂ , R23.	1) First part of study concludes that derived dimensionless parameters were accurate for water. 2) Second part of study concludes that derived dimensionless parameters were accurate for CO ₂ , Ammonia and R23 along with water.
Chatoorgoon (2008)	Examined supercritical flow instability in two identical horizontal parallel channels and derived stability boundary equation. Code: A 1-D non-linear in-house program (SPORTS). Fluid: Water.	1) The proposed stability boundary criteria were accurate enough for the prediction of flow instability boundary with just requiring steady state. 2) The importance of the accuracy of state equation for the prediction of supercritical flow

		instability was pointed out. 3) This study pioneered research in parallel channels.
Sharabi et al. (2008)	Analysis of supercritical fluid in a single heated channel. Code: CFD, FLUENT. Fluid: Water.	1) The study showed the performance of the CFD code FLUENT to predict the unstable behavior in a single channel flow. 2) This was first reported work using CFD software.
Sharabi et al. (2009)	The stability analysis of SCWR rod bundle sub-channels. Code: CFD, FLUENT. Fluid: Water.	1) The characteristics of density wave oscillations in triangular and square pitch assemblies were similar to those of circular channels.
Yeylaghi et al. (2011)	Assessment of dimensionless parameters for static instability in supercritical down-flow channels. Code: 1-D linear program. Fluid: Water, CO₂	1) Chatoorgoon dimensionless parameters correlated well with the numerically predicted data. 2) Down-flow is most stable orientation compared to horizontal or vertical up-flow.
Su et al. (2012)	Examined the flow instability in two vertical parallel channels with supercritical water. Code: A 1-D non-linear in-house program (TIMDO). Fluid: Water.	1) The flow instability in two vertical parallel channels occurs when any disturbance to mass flow is not absorbed by the interaction of pressure drop and distribution of mass flow in

		the channels. 2) Channel inlet temperature increase showed the non-monotonic behavior on flow stability boundary.
Chatoorgoon (2013)	Derived the dimensionless parameters for the static flow instability. Code: A 1-D non-linear in-house program. Fluid: Water.	1) The proposed dimensionless parameters were accurate enough for the prediction of flow instability boundary, with just requiring steady state run. 2) Static instability is more likely to occur in the down-flow and least in the up-flow. 3) Low temperatures are the favourable conditions for occurrence of static instability.
Ampomah-Amoako & Ampomah-Amoako et al. (2013)	A series of flow instability studies in 3-D nuclear reactor sub-channels and a 1-D heated channel. Code: CFD, STAR-CMM+ and 1-D, RELAP5. Fluid: Water.	1) The study gave an insight into the development of the CFD methodology and confirmed the capability of the CFD code to predict the unstable flow behavior. 2) Vertical up-flow, vertical down-flow and horizontal flow were all studied using STAR-CCM+ and 1-D code, RELAP5. 3) The results from two codes were found to be in

		very good agreement. 4) It was suggested that the flow instability phenomena were mainly characterized by 1-D flow behavior.
Xiong et al. (2013)	Numerically analyzed the experiments performed by Xiong et al. (2012). Code: A 1-D non- linear in-house program. Fluid: Water.	1) The numerical and experimental results agreed with an error between 3-12%. 2) Effect of inlet temperature was found to be non-monotonic, which is well know for two phase flow instabilities, concluding the mechanism of two-phase flow instabilities and supercritical flow instability are alike.
Debrah et al. (2013a,2013b)	Examined the influence of the heat-wall storage on flow stability boundary with a natural circulation loop. Code: A 1-D non-linear in-house program.	1) The study concluded that considering wall-heat storage largely increases the stability boundary. It was recommended not to include the wall-heat storage effect. 2) The further study with improved heat transfer correlation was suggested.
Xi et al. (2014a)	Numerically analyzed experiments performed by Xiong et al. (2012). Code: CFD-ANSYS. Fluid: Water.	1) The CFD results were closer to experiment data than 1-D results; therefore, better predict flow instability boundary. 2) The parametric effect on the flow stability

		boundary is different in 3-D and 1-D analyses. 3) Further study with improved CFD model was suggested.
Li et al. (2014)	Examined supercritical flow instability in a single and parallel channel. Code: APROS (1-D non-linear). Fluid: Water.	1) The agreement between the predicted and previous study results was between an error 3-8%. 2) This has shown the ability to use APROS simulation software to accurately predict the onset of unstable flow behavior. However, the software gave a discrepancy in predicting the accurate oscillation period. 3) There exists an inflection point with channel inlet temperature increase.
Dutta et al. (2015)	Examined in-phase and out- of -phase mass oscillations in CANDU reactor. Code: A 1-D non-linear in-house program. Fluid: Water.	1) The out-of-phase mode was having less stable zone compared to the in-phase mode. 2) Increasing asymmetric power distribution between channels makes reactor unstable. 3) Increasing inlet pressure drop coefficient makes reactor stable.
	Studied the influence of the heat-wall storage on flow	1) The inclusion of heat-wall storage increases the

Sharma et al. (2015)	stability boundary with a natural circulation loop. Code: A 1-D non-linear in-house program (NOLSTAP). Fluid: Water.	stability of the system largely.
Ebrahimnia et al. (2016)	Examined static and oscillatory flow instability in a single vertical up-flow channel. Code: CFD- ANSYS. Fluid: Water.	1) Results were in good agreement with the 1-D non-linear SPORTS results. 2) Selecting the different turbulence model in CFD modeling does not affect instability boundary.
Shitsi et al. (2017)	Examined supercritical flow instability in a two vertical up-flow parallel channel. Code: CFD-STAR-CCM+. Fluid: Water.	1) Results were in good agreement with the experimental data. 2) It was also reported that amplitude of out-of-phase oscillations is significantly affected by system parameters. However, the system parameters do not affect the period of oscillation.
Li et al. (2018)	Numerically analyzed the experiments performed by Xiong et al. (2012). Code: CFD-ANSYS. Fluid: Water.	1) Found that the 1-D non-linear results were closer to the experiment data compared to the 3-D results. This is contradicting to previous finding of Xi et.al (2014a). Discrepancy was because poor temporal convergence by Xi et al.

		(2014a) 2) Recommended using first order transient scheme in CFD modelling as second order transient scheme were not smooth. But later, Ghadge (2018) revealed that unsmooth curves were hidden oscillations.
Liu et al. (2018)	Examined the effect of heat-wall storage on the flow instability boundary using a single vertical up-flow channel. Code: A 1-D non-linear in-house program. Fluid: Water.	1) With the inclusion of heat-wall storage, the system becomes more stable. 2) System become more stable if wall thickness is increased. 3) There exists a critical length for a pipe, below which the flow stability decreases with pipe length. Above the critical length, the flow stability remains constant with no inclusion of wall-heat storage and increases with the inclusion of wall-heat storage, with pipe length increase.
Ghadge (2018)	Numerically analyzed the performed vertical parallel channels instability experiments. Code: CFD- ANSYS, 1-D Linear SPORTS. Fluid: Water.	1) The 1-D linear results were closer to the experiment data compared to the 3-D results. This is similar finding to Li et al. (2017) but contradicting with Xi et al. (2014a).

		2) They concluded that frequency domain solution better predicts the flow instability boundary than time domain solution. 3) Recommended using smaller time step, second order transient scheme, full geometry and inclusion of wall-heat storage for the better prediction of 3-D CFD results. 4) FFT analysis revealed the hidden oscillation period of 5 seconds for Xiong et al. (2012) experiments, which explains the previous predictions about the oscillation period of 5 seconds predicted by various 3-D non-linear studies.
Saini (2019)	Assessed the credibility of the licensed software CATHENA to predict unstable behavior in two heated parallel channels. Code: CATHENA (v.3.5.4.4). Fluid: Water and CO₂.	1) CATHENA predicted the reasonable threshold power for nearly half of studied cases; however, for remaining cases the error was large. 2) CATHENA was unable to predict the correct experimental oscillation period. 3) CATHENA predicted unrealistic results with wall-heat storage effect. Therefore, it was

		concluded CATHENA performance with wall-heat storage is inaccurate.
Ghadge et al. (2020)	Examined the effect of heat-wall storage on flow instability boundary in two vertical up-flow parallel channels. Code: A 1-D linear in-house program. Fluid: Water.	1) The inclusion of the heat-wall storage has small amount of effect on the flow instability boundary for two different parallel channels; however, the effect is considerable large for a single channel. 2) For two identical parallel channels, inclusion of heat-wall storage does not affect the instability boundary because of the cancellation effect. 3) The prediction of the threshold power and oscillation period improved using wall-heat storage when modelling actual experiments. 4) This was first reported work that had good agreement with experiments using wall-heat storage.

Table 2.2: Experimental summary of channel supercritical flow instability.

Reference	Fluid	Test Section Configuration	Operating Conditions Range	Findings and comments
Akagawa,	R-113	Length: 4000 mm	Temperature: Varying	1) Experimental results agree well with

et al. (1971)		ID: 4 mm Material: Copper tube No. of channels: 1-3	Pressure: atmospheric - supercritical pressure.	the simple stability boundary criteria proposed in investigation.
Xiong et al. (2012)	Water	Length: 3000 mm ID: 6 mm OD: 11 mm Material: INCONEL 625 No. of channels: 2	Temperature: 180 – 240 ° C Pressure: 23 – 25 MPa Mass Flow: 600 – 800 kg m ⁻² s ⁻¹ K-factors Inlet: 5.4, 5.5 K-factors Outlet: 4.93, 6.46	1) Provided the valuable instability data for the validation of existing software or develop new programs. 2) Increasing system pressure stabilizes the system flow, whereas increasing channel inlet temperature destabilizes the system flow. The inflection point for channel inlet temperature increase was not reached because of limitation with experimental facility.
Xi et al. (2014b)	Water	Length: 3150 mm ID: 6 mm OD: 19 mm Material: INCONEL 625 No of channels: 2	Temperature: 180 – 260 °C Pressure: 23 – 25 MPa Mass Flow: 125 -145 kg/hr K-factors Inlet: 4.1, 4.3 K-factors Outlet: 3.9, 3.8	1) Provided the valuable instability data for the validation of existing software or develop new programs. 2) Three power profiles were studied: axially increased, axially decreased and uniform power profile. However, study of power profiles

				was unrealistic from reactor's viewpoint, as in reactor power variation is gradual, not a sudden large step. 3) The axially increased power shape was the most stable power shape followed by uniform and axially decreased power shape.
Wang et al. (2018)	Water	Length: 4000 mm ID: 25 mm OD: 28 mm Material: 1Cr18Ni9Ti No of Channels: 2	Temperature: 200 – 390 °C Pressure: 23 – 30 MPa Mass Flow: 0.05 – 0.2 kg/s K-factors Inlet: 0-5.5	1) Increasing pressure, inlet pressure drop coefficient and mass flow rate are favourable conditions to make the system flow stable. 2) Increasing inlet temperature destabilizes the system flow.
Yang et al. (2018)	Cyclohexane	Length: 0.20 - 0.79 m ID: 1.0 - 2.0 mm Material: 316 Stainless steel	Temperature: 30 – 70 °C Pressure: 4.5 – 5.5 MPa Mass Flow: Details not provided. K-factors: Details not provided.	1) Decreasing the tube length can improve the flow stability of the system. 2) Increasing the tube diameter can improve the flow stability of the system.
Saini et al.	CO ₂	Length: 1500 mm	Temperature: 7.3 – 30.8 °C	1) Provided the valuable instability

(2020)		ID: 16.56 mm OD: 19.05 mm Material: INCONEL 825 No. of channels: 2	Pressure: 7.4 – 9.1 MPa Mass Flow: Varying Range K-factors (Inlet and Outlet): Varying Range	data of wider range for the validation of existing software or develop new programs.
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Chapter 3 Experimental Setup and Test Procedure

3.1 Introduction

To enrich the limited experimental database of supercritical flow instability in parallel channels, the experimental setup of two vertical parallel channels was constructed at the University of Manitoba, designed by Dr. Vijay Chatoorgoon, manufactured by the STERN laboratories in 2013. This experimental setup was assembled in the Energy Lab – 103 at the University of Manitoba. The purpose of the experimental facility was to capture instability boundaries (the power at which the mass flow rate in channels starts oscillating) under different system conditions. The working fluid used was CO₂. CO₂ was chosen over water because of its low critical point temperature and pressure. The critical pressure and temperature of CO₂ is 7.37 MPa and 31 °C, whereas for water it is 22.064 MPa and 374 °C. Figures 3.1 and 3.2 show the trend of change of the properties across pseudo-critical point for CO₂ and water. It is apparent that density, specific heat, viscosity, and thermal conductivity change across pseudo-critical point follows almost the same trend for both CO₂ and water, making CO₂ a good substitute for water.

The main flow was driven by natural-convection forces as money for a pump was not available. However, natural circulation was not a factor in the channel instability as we ensured that the main flow to the inlet header was steady in all cases. The details of the experimental facility are discussed in the following sections.

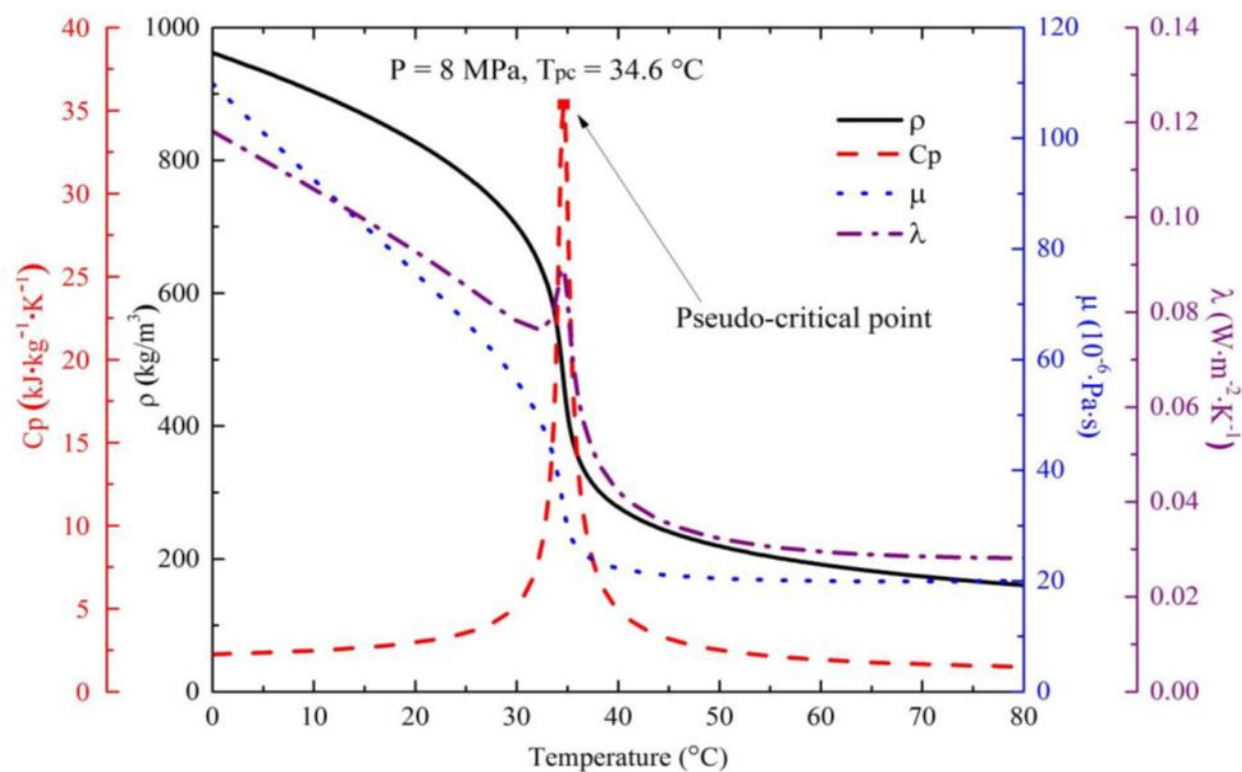


Figure 3.1: The change of the properties of CO₂ across the Pseudo-critical point.

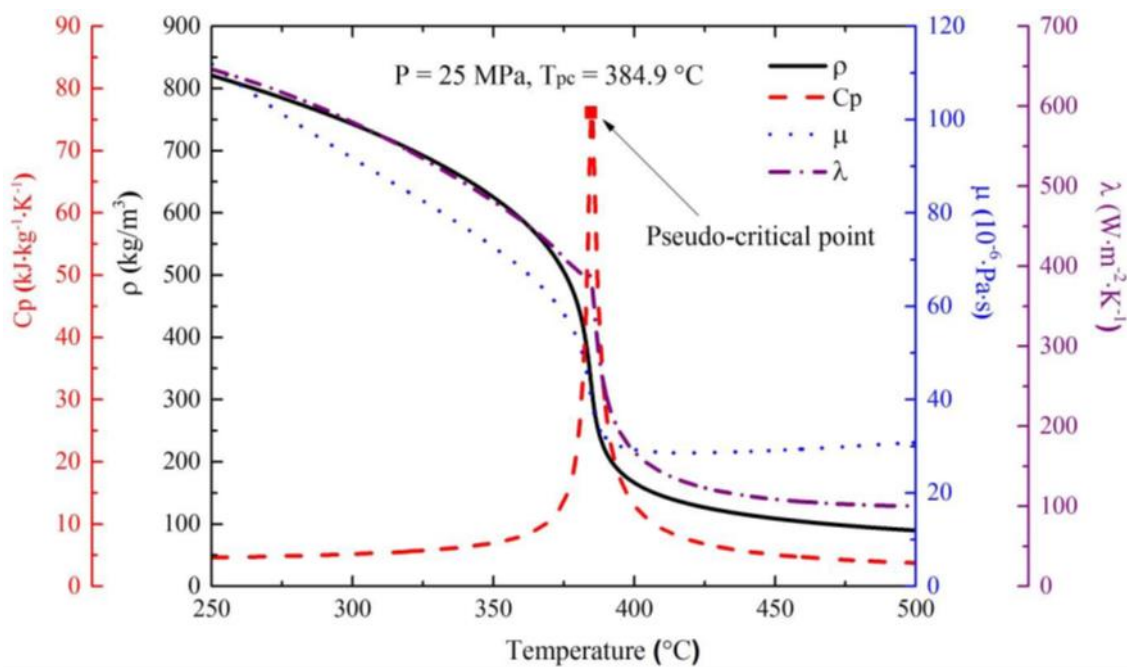


Figure 3.2: The change of the properties of water across the Pseudo-critical point.

3.2 Experimental Setup

Figure 3.3 shows the flow process diagram of the experimental facility with its main systems and components like primary flow system, secondary flow system, evacuation system, pressure system, flow meters, ball valves and so on.

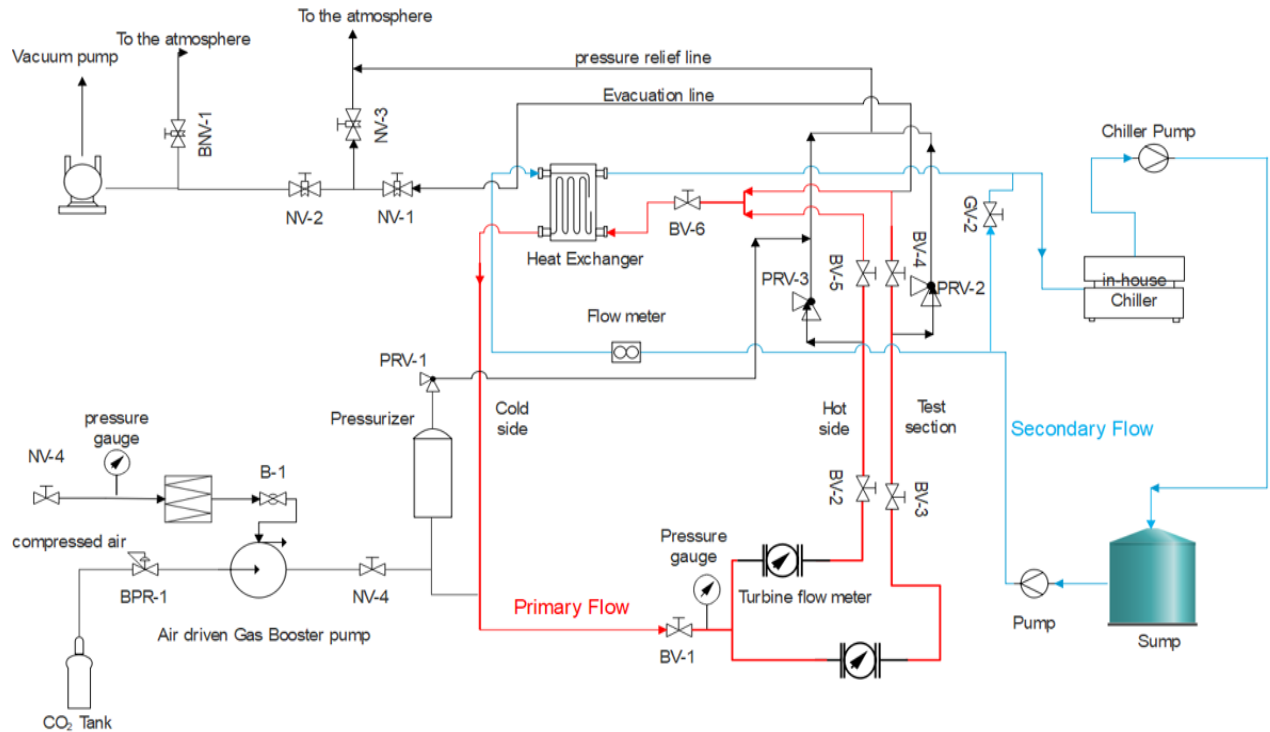


Figure 3.3: Flow process diagram of the experimental facility.

The different systems that the experimental facility comprises are:

1. The primary flow system
2. The secondary flow system
3. The evacuation system
4. The pressure system
5. The power supply system
6. The data acquisition system

7. The safety system

3.2.1 The Primary Flow System

The primary flow system is a closed loop in which the working fluid, CO₂ circulated. Figure 3.4 shows the schematic diagram of the primary flow system. The loop is a rectangular geometry having a riser length of 2670 mm and a horizontal length of 1497 mm. It mainly consists of the test section, heat exchanger, flanges, pipes and pipe fittings like couplings, elbows and so on. The details about the components provided by the manufacturer used in building the primary loop can be found in Table 3.1. Each channel consists of vertical and horizontal entry section, flow meter, inlet and outlet valves and riser section. Both channels were connected to a common lower and common upper plenum. A turbine flow meter was installed on the horizontal entry section, and ball valves were installed at the inlet and the outlet of each channel. The whole loop was insulated with Super wool fiber to reduce the heat loss to the surroundings.

Figure 3.5 shows the schematic diagram of the test section. The test section consists of two vertical parallel channels made up of INCONEL 825 having inner and outer diameter 16.56 mm and 19.05 mm, and length 1500 mm. The length and diameter of vertical entry and riser section are 500 mm and 20.56 mm respectively, and that of the horizontal entry section is 560 mm and 26.67 mm. The diameter of the lower and upper plenum is 76.2 mm. The reason for using INCONEL 825 material for the test section channels was to ensure a uniform distribution of the heat flux as INCONEL has a minimal change in resistance to temperature changes. It also has excellent corrosion resistance. A uniform power was applied axially to the test section channels through a rectifier and incremented in small steps. However, a small power difference was established naturally between the channels, which was beyond our control. A plate type heat

exchanger was used to remove the heat applied to the working fluid. The heat exchanger can dissipate a maximum 32 kW of power.

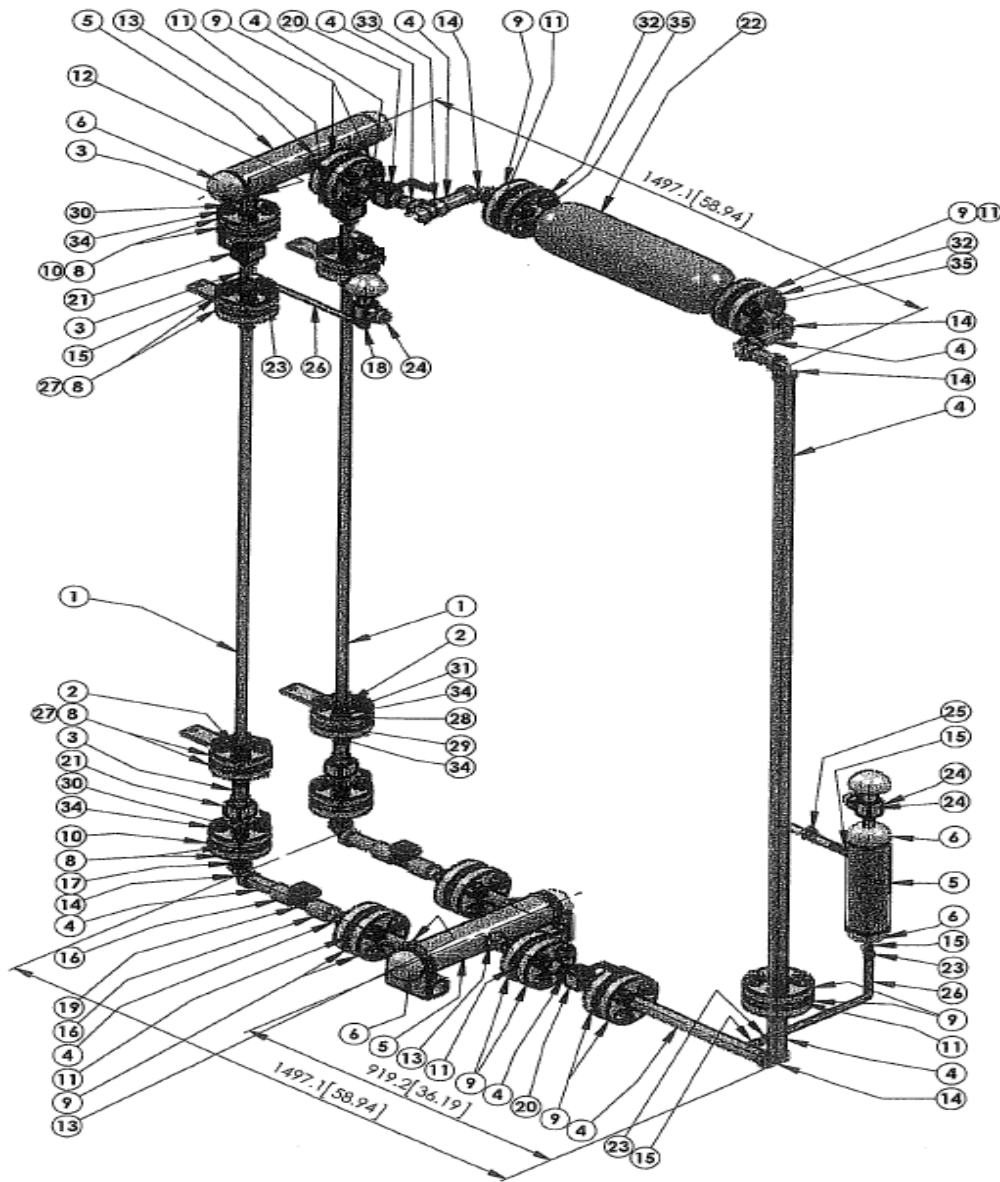


Figure 3.4: Schematic diagram of the primary loop.

Table 3.1: List of items used in building the primary loop.

QT'Y	Item	Description	Material
1	1	T/S TUBE: $\frac{3}{4}$ " OD $\times$ 0.049" THK WALL	INC 825
4	2	RING: MAKE FROM $\frac{3}{4}$ " SCH.80 PIPE	SA-312 TP316
1	3	PIPE: $\frac{3}{4}$ " SCH.40 SMLS	SA-312 TP316
1	4	PIPE: 1" SCH.40 SMLS	SA-312 TP316
1	5	PIPE: 3" SCH.40 SMLS	SA-312 TP316
6	6	CAP: 3" SCH.40	
16	8	FLANGE: $\frac{3}{4}$ " 1500# SW SCH.40 BORE	SA-182 F316
16	9	FLANGE: $\frac{3}{4}$ " 1500# SW SCH.40 BORE	SA-182 F316
4	10	GASKET: $\frac{3}{4}$ " 1500#	
11	11	GASKET: 1" 1500#	
2	12	SOCKOLET: $\frac{3}{4}$ " $\times$ 3" 3000#	SA-182 F316
4	13	SOCKOLET: 1" $\times$ 3" 3000#	SA-182 F316
8	14	ELBOW: 1" 90° 3000# SW	SA-182 F316
6	15	COUPLING: $\frac{1}{4}$ " NPT 3000#	SA-182 F316
4	16	THREADED COUPLING: 1", 3000#	SA-182 F316
2	17	REDUCER MALE CONNECTOR: SOCKET	SA-182 F316

		WELD, 1" × ¾", 3000#	
2	18	SWAGELOK FITTING: 3/8" TUBE × ¼" NPT	
2	19	TURBINE FLOW METER: 1" OMEGA FTB-1421	
1	20	MILWAUKEE BALL VALVE: 1" MODEL #35-SS-0F-06-LL	
4	21	MILWAUKEE BALL VALVE: ¾" MODEL #35-SS-0F-06-LL	
2	22	PLATE TYPE H.E	
5	23	SWAGELOK-0.25 NPT MALE × 0.375 TUBE	
3	24	SAFETY RELIEF VALVE: SET AT 1650 PSI @204 °C	
1	25	VALVE: 3/8" SWAGELOK	
	26	3/8" × 0.049" THK TUBE	SA-312-TP304
4	27	INSULATING GASKET (FOR ¾" 1500# FLANGE)	1/8" THK PHENOLIC
32	28	INSULATING WASHER	1/8" THK PHENOLIC
16	29	INSULATING SLEEVE	1" DIA. GLASS FILLED TEFLON
16	30	STUD: 3/4"-10 UNC × 4.25" LG	SA-193 B7
16	31	STUD: 3/4"-10 UNC × 4.5" LG	SA-193 B7

88	32	HEX NUT: 7/8-9 UNC	SA-194-2H
2	33	TEE 1.0" 3000# SW	SA-182 F316
64	34	HEX NUT: ¾-10 UNC	SA-194-2H
45	35	STUD: 7/8"-10 UNC × 5" LG	SA-193 B7

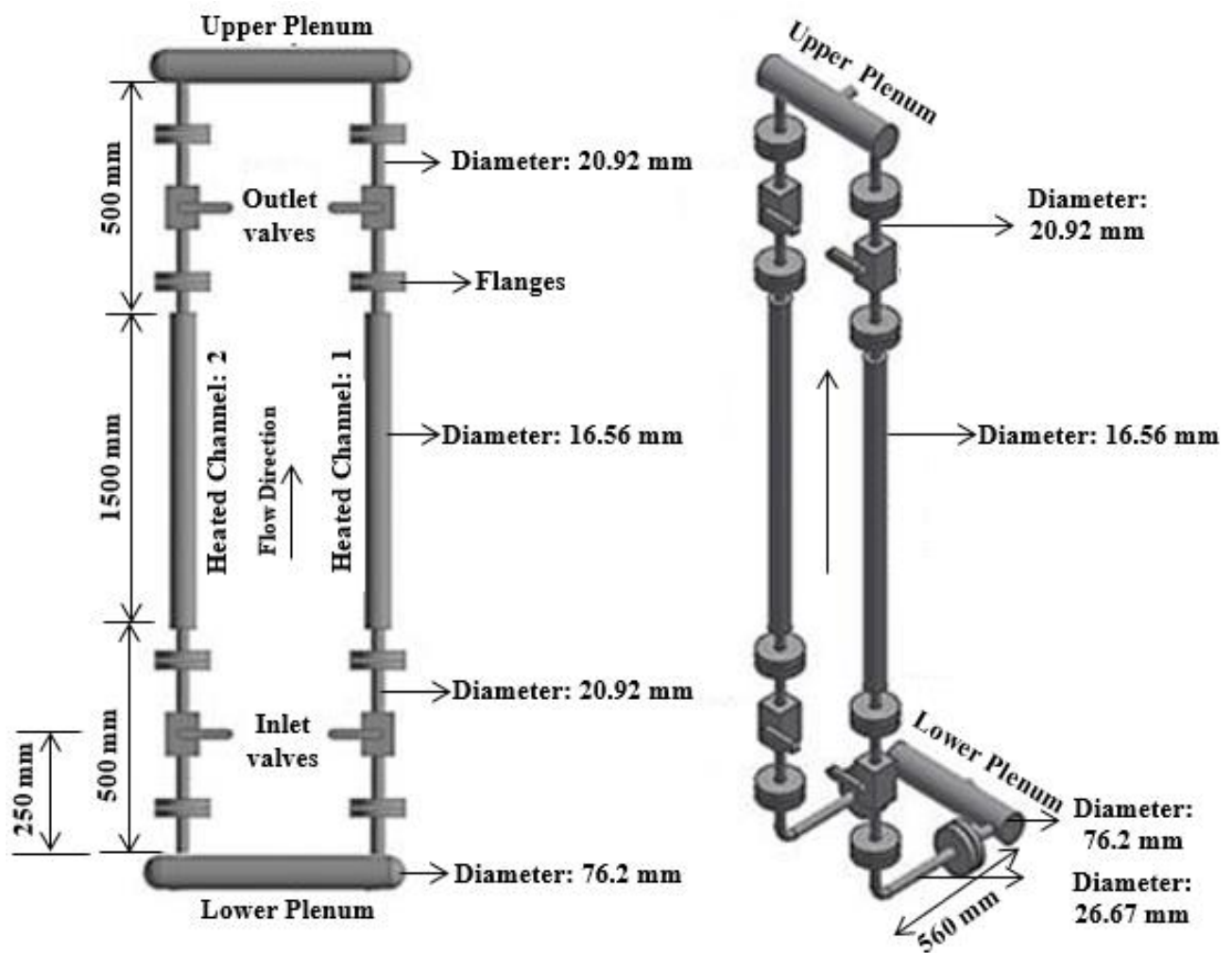


Figure 3.5: Schematic diagram of the test section.

3.2.2 The Secondary flow system

The secondary flow system is a cooling system that consists of a pump, roof-top chiller, sump and gate valves. Figure 3.6 represents the flow process diagram of the secondary flow system. The working fluid (coolant) was a solution of Propylene glycol mixed with water. A pump was the driving force. The coolant from the sump using pump was passed through the heat exchanger where it extracted the heat from the working fluid circulating in the primary loop. After that, it was passed through the rooftop chiller where the heat was released to the environment, before returning to the sump. The inlet temperature of the supercritical CO₂ was maintained constant by regulating the mass flow rate of the coolant with the help of the gate valve (later, it was replaced by the needle valve for more accuracy and control).

Figure 3.7 shows the diagram of the rooftop chiller. The rooftop chiller is an air-cooled heat exchanger that uses the cold atmospheric air to cool the coolant. In wintertime the ambient temperature can go as low as -25 °C; this makes it excellent for cooling. In the summertime, the ambient temperature is high, making the roof-top chiller ineffective for use. The roof-top chiller was assessed by Dr. Vijay Chatoorgoon and installed by Khan (2015) and more details can be found there.

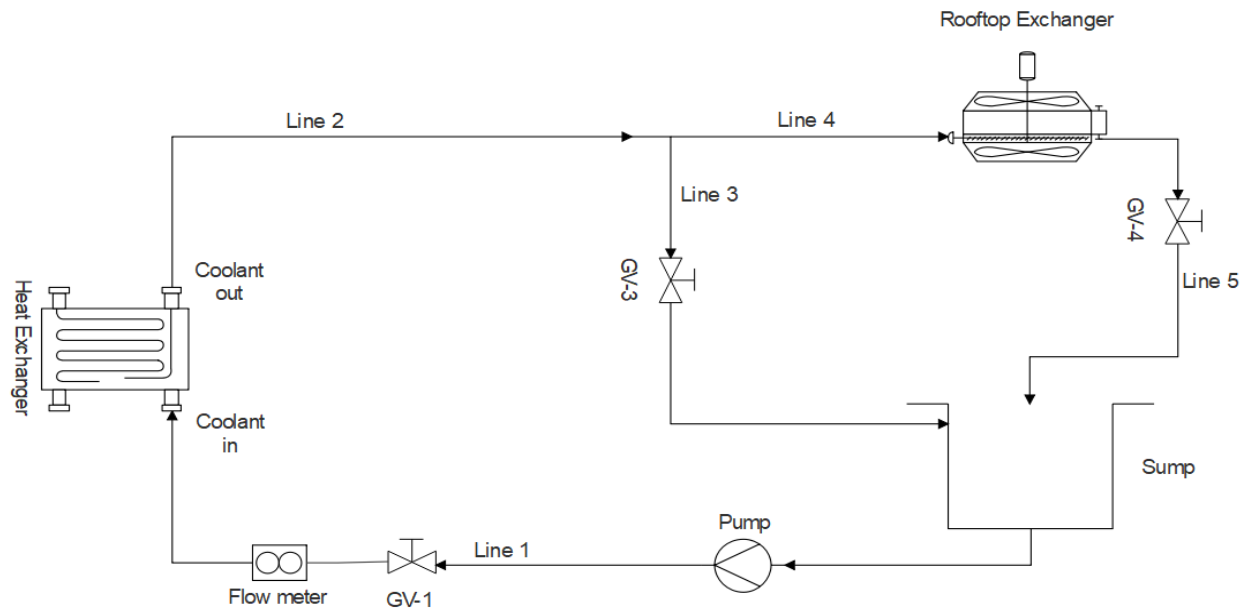


Figure 3.6: Flow process diagram of secondary flow system.



Figure 3.7: Rooftop chiller.

3.2.3 The Evacuation System

The purity of the working fluid (CO_2) is of the utmost importance in the experiment, as minor contaminants can lead to inaccurate results. To avoid any contamination in the working fluid, vacuuming of the loop was done before filling it with CO_2 . Figure 3.8 shows the flow process diagram of the vacuuming system. It consists of the vacuum pump, needle valves, and pipelines connecting the primary loop. The loop was vacuumed in three intervals, 3 hours each, with a 30 minutes rest between intervals to cool the vacuum pump.

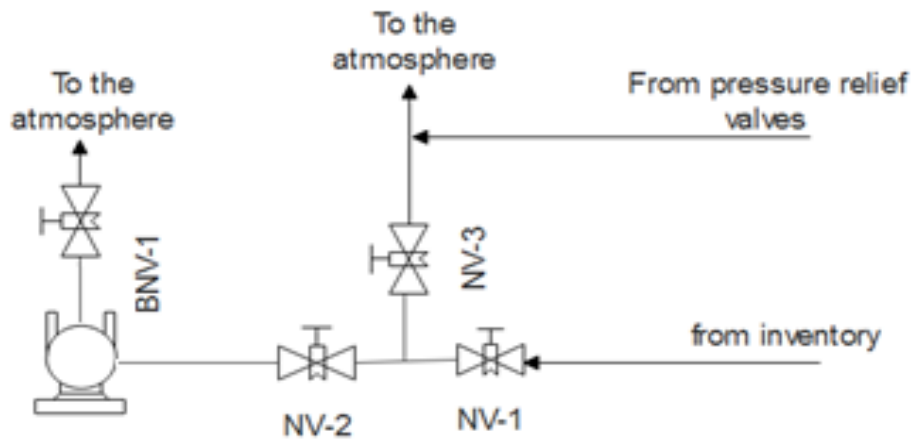


Figure 3.8: Flow process diagram of the vacuum system.

3.2.4 The Pressure system

The pressure system consists of a pressure control system and the pressurization system.

3.2.4.1 The pressure control system

The pressure control system consists of the accumulator, helium gas tank, back-pressure regulator, single-stage pressure regulator, glass fitted containment connected to the accumulator,

and check valves. This control system was not used in the current study because Saini (2019) found that the helium gas escapes into the primary loop because of the small size of the accumulator. For economic reasons, a new accumulator of larger size was not acquired. Instead, two-needle valves NV-1 and NV-3 were used to manually release the excess pressure from the primary loop to the atmosphere. This was the most cost-effective way to maintain a constant pressure in the loop.

3.2.4.2 The Pressurization system

The pressurization system consists of the gas booster pump, CO₂ tank, bucket of propylene glycol solution, and a needle valve. The gas booster pump was used to pump the CO₂ from the cylinder to the loop. A propylene glycol solution was used to cool the hose connecting the booster pump and the loop inlet, which gets heated up during booster pump operation.

3.2.5 The Power supply system

The electrical power to the channels was supplied by a 30-kW rectifier, which was donated by Atomic Energy of Canada Limited (AECL), now known as Canadian Nuclear Laboratories (CNL). The test channels, which act as resistors, heats up when current passes through them. A circuit breaker of 1500 Amps was installed between the test channels and the rectifier. The power supplied to the channels was controlled by scrolling the wheel of the mouse in the LabVIEW software, designed by Kalsi (2017). Figure 3.9 shows a picture of the rectifier used in the power supply system.



Figure 3.9: Rectifier.

3.2.6 The Data Acquisition System

The data acquisition (DAQ) system samples the signals from the instruments that measure real-world physical conditions and converts these signals into digital values that are processed by a computer. The main components of the data acquisition system are the sensors, signal conditioning, DAQ module, wires, and display devices. In the current experiments, the sensors measure the real-time conditions such as the temperature, pressure, mass flow rate and power, and these measured signals are transmitted to the DAQ module via wires. The DAQ module converts the measured signals into machine signals, which were manipulated by the PC and all parameters are displayed on the LabVIEW software for recording. This data acquisition system

was designed and installed by Kalsi (2017) and more details can be found there. Figure 3.10 shows the block diagram of the data acquisition system (DAS).

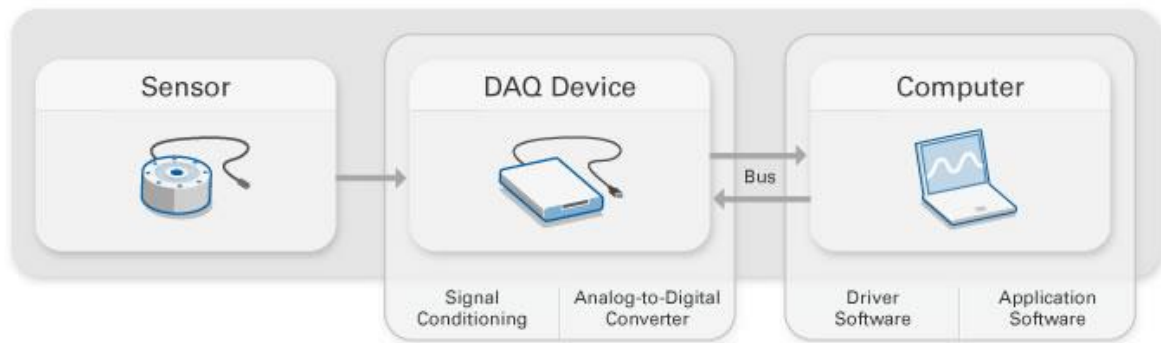


Figure 3.10: Block diagram of the data acquisition system.

3.2.7 The Safety System

Safe working conditions were given top priority in our work environment. There were various safety features installed in the experimental setup. The pressure relief valves were installed in the primary loop for releasing the pressure automatically when the loop pressure exceeds 11.38 MPa. Besides this, the experimental setup is surrounded by a Perspex containment which protects the operator from blasts, which is possible due to the high pressure.

The doors of the Perspex containment also act as a limit switch, which ensures that the current is supplied to the test section only when the doors are closed. If any of the two doors remained open accidentally during the operation, the circuit breaks and the rectifier shut down automatically.

Another safety feature is the lock-key, which ensures that power is only supplied to channels when the key is in the lock and turned ON. Also, there was an emergency stop button that can be used if any sudden complication arises during operation. It immediately shuts down the whole experiment when pressed. The safety feature programmed in the LabVIEW software shuts down the experiment automatically when the loop pressure and wall temperature of channels exceed the 10.34 MPa and 450 °C. Figure-3.11 shows the Perspex containment, lock-key, and emergency stop button.



Figure 3.11: Safety Features of the experimental facility.

3.3 Instrumentations

Various instruments were used in the experimental setup to measure the wall temperature, fluid temperature, volume flow rate of CO₂, loop pressure, pressure drop, coolant flow rate, and

voltage drop in the test section. Table 3.2 summarizes the details of the instruments used in the loop.

Table 3.2: Details of instruments used in the experimental setup.

Instrument	Details	Purpose
Thermocouple	OMEGA Engineering, Type: T-type, 1/8” sheath diameter	Fluid temperature measurement
Thermocouple	OMEGA Engineering Type: K-type, 1/8” sheath diameter	Wall temperature of the test section
Absolute pressure transducer	Validyne Engineering Corporation Range: 0-1500 psi	Absolute pressure measurement of fluid contained in the loop
Differential Pressure Transducer	Validyne Engineering Corporation Model: P55 Range: 0-0.5 Psi	Pressure drop measurement across heat exchanger
Differential Pressure Transducer	Validyne Engineering Corporation Model: P55 Range: 0-8 Psi	Pressure drop measurement across valves
Differential Pressure Transducer	Validyne Engineering Corporation Model: DP303 Range: 0-5 Psi	Pressure drop measurement across the heating channel
Turbine Flow Meter	OMEGA Engineering Model: FTB-1421 Range: 0.6~3 GPM	Supercritical CO ₂ volumetric flow rate measurement

Turbine Flow Meter	Seametrics Model: SPX-050 Range: 0.6 ~ 40 GPM	Coolant volumetric flow rate measurement
Isolated DC Voltmeter	Wilkerson Instrument Corporation Model: SR2101 Range: 0 ~ 20 V	Measuring the voltage drop across the test section
Dial pressure gauge	Swagelok Pressure Gauge Range: 0~1500 psi	System pressure measurement.

3.3.1 Temperature Measurement

Ten T-type thermocouples were used to measure the fluid temperature, and ten K-type thermocouples were used to measure the wall temperature of the test section channels. Figure-3.12 shows the placement of the thermocouples in the experimental facility (subscript TT is used for T-type thermocouple, and TK is used for K-type thermocouple). The K-type thermocouples have an uncertainty of ± 1 °C and can measure the temperature range from -200 to +1350 °C. The T-type thermocouples have an uncertainty of ± 0.5 °C having temperatures range from -270 to 370 °C.

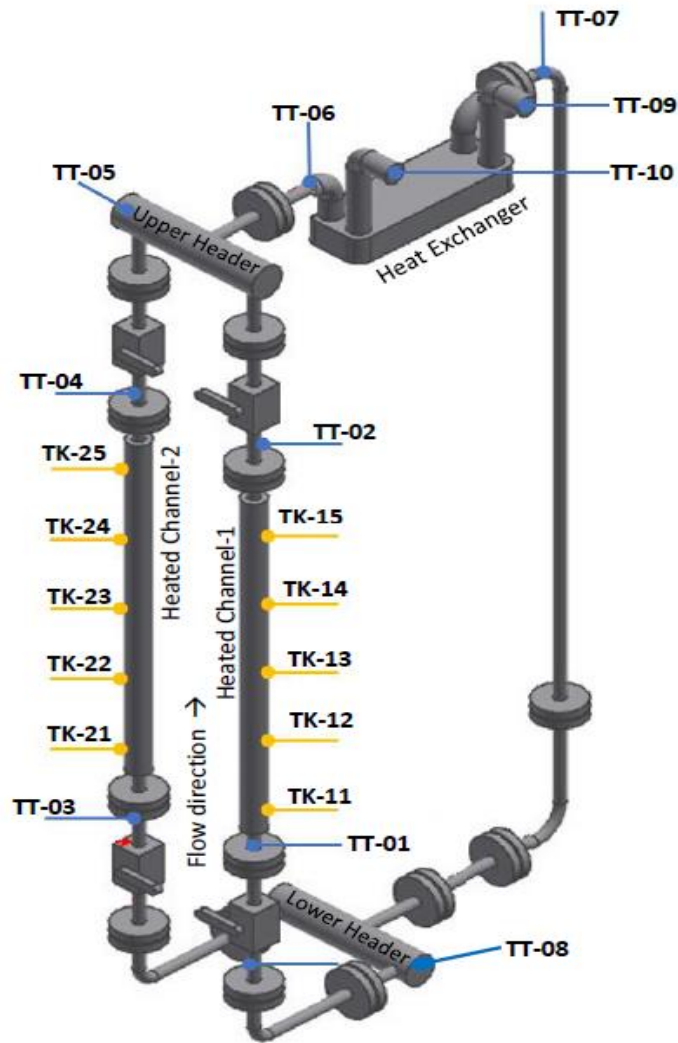


Figure 3.12: The placement of the thermocouples in the experimental facility.

3.3.2 The Pressure and Pressure-Drop Measurement

The loop pressure was measured with the aid of an absolute pressure transducer installed at the inlet plenum; it has a pressure range of 0 ~ 1500 Psi (0- 10.34 MPa). Additionally, a dial pressure gauge of the same pressure range was also installed at the inlet plenum. Differential pressure transducers were installed to measure the pressure drop across the inlet and outlet of the ball valves, heated channels, and the heat exchanger. The differential pressure transducer has an

uncertainty of $\pm 4\%$ and excellent response time (0.05 sec.). These differential transducers were calibrated prior to the experiments, and they were installed by Kalsi (2017). Figure-3.13 shows the placement of the differential pressure transducers.

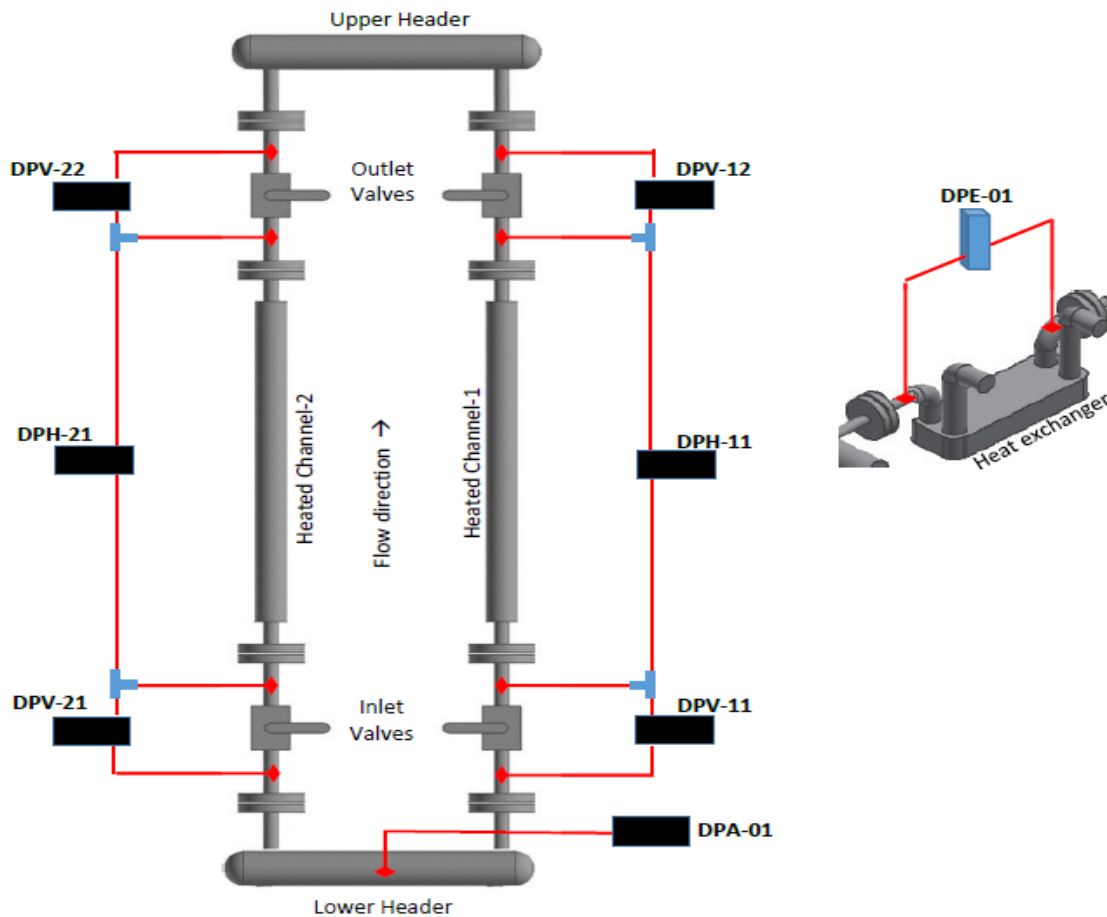


Figure 3.13: Placement of the DP cells.

3.3.3 Flow Measurement

The flow rate of CO_2 in the test channels was measured with a turbine flow meter installed at the entry of each channel. One turbine flow meter was also installed in the secondary line to measure

the coolant flow rate. The turbine flow meters measure the flow rate in litre per minute (LPM). When the fluid passes through the flow meter, the vanes of the turbine rotate with a frequency proportional to the fluid velocity. The rotation of the vanes is converted into AC pulses, and these pulses produce the output frequencies that are displayed on the DPF700 rate meter. The DPF700 rate meter also converts the electrical signals to 4 ~ 20 mA analog output and this current signal, when combined with the 250-ohm resistor, produces 1 ~ 5 V voltage signal which is transmitted to the DAQ module. The DAQ module sends the signal to the computer that is displayed in the LabVIEW software, in litre per minute (LPM). The formula used to calculate the volumetric flow rate is:

$$LPM = \frac{Hz * 60}{NK} \quad (3.1)$$

Where Hz is the frequency of the rotating vanes, NK is the manufacturer calibrated flow coefficient, and LPM is the volumetric flow rate (Litre per minute). Similarly, the turbine flow meter installed in the secondary line measured the coolant flow rate works on the same principle as discussed above. Figure 3.14 shows the flow meter signal flow.

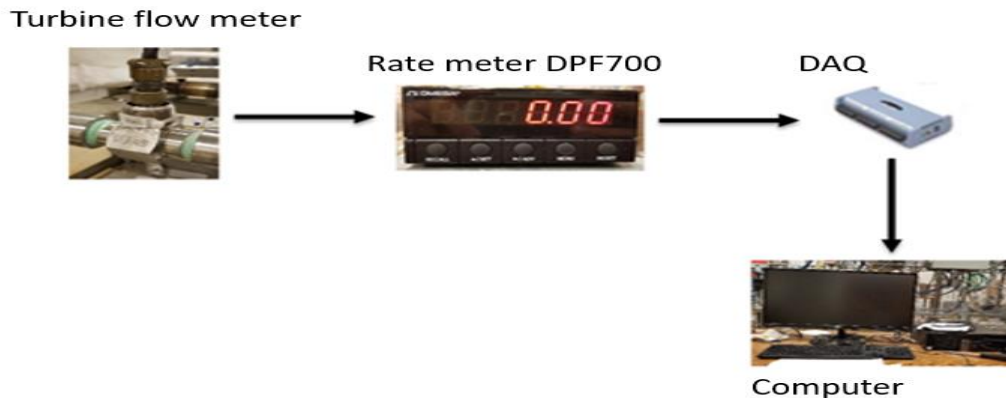


Figure 3.14: The flow meter signal flow.

3.3.4 The Electrical Power

The electrical resistance of the test section converts the electrical power supplied by the rectifier into heat, thus heating the channels. An isolated DC voltmeter was used to measure the voltage drop across the test section. The electrical power was calculated by using the formula:

$$P = \frac{V^2}{R} \quad (3.2)$$

Where V is the voltage drop, R is the electrical resistance of INCONEL 825 in ohm, and P is the power in watts (W).

3.4 Instrumental Uncertainties

No physical quantity can be measured exactly. Always some amount of uncertainty is present, and one can measure the quantity within a certain range of uncertainty. This fact can be represented in the standard form $x \pm dx$. This means x is between $x + dx$ and $x - dx$. Table 3.3 shows the uncertainties in measurements. This data was provided by the manufacturer.

Table 3.3: Uncertainty in measurement

Parameter	Uncertainty
Flow measurement	$\pm 3\%$
Fluid Temperature measurement	$\pm 0.5\%$
Wall temperature measurement	$\pm 1\%$
Electrical Power to Test Section	$\pm 2.2\%$
Pressure measurement	$\pm 0.5\%$
Pressure-drop measurement	$\pm 4\%$

3.5 Test Preparation

Test preparation mainly consists of calibrating the DP cells, performing a leakage test, vacuuming the loop, and checking all instruments before conducting the experiments. These test preparations were done to ensure accurate results.

3.5.1 Calibrating DP Cells

It is the process of adjusting the sensed electrical signal to know the relationship with the applied pressure. A pressure calibrator was used to calibrate the DP cells. Firstly, DP cells were disconnected from the loop and + and – terminals of the DP cells were connected to the calibrator, and the values of zero and span were set. When zero pressure was applied the DP cell sends the 0 Vdc output signal and when full span pressure was applied, DP cell sends the +10 Vdc output signal. Details on the installation and calibration of DP cells can be found in Kalsi (2017).

3.5.2 Leakage Test

A leakage test was performed to ensure that there was no leakage in the loop. Initially, the loop was pressurized to 3.5 – 3.8 MPa and was left undisturbed for 1 hour, and the pressure was noted. Further, the loop was again left undisturbed for 3-4 days and again the pressure was noted. If there was considerable pressure drop like (0.8 ~ 1 MPa), then a soap solution was sprayed on the fittings, valves, fitting of DP cells, and thermocouples. Bubbles would form at the leakage spot if there were a leak. This was how the leakage point was detected and fixed.

3.5.3 Vacuuming the loop

After performing, the successful leakage test, vacuuming of the loop was done. Initially, the CO₂ present in the loop after the leakage test was released to the atmosphere by opening the NV-1

and NV-3 valves. After this, NV -3 was closed and NV -2 was opened, and the vacuum pump was turned ON. The loop was vacuumed in three intervals, 3 hours each, having 30 minutes rest after each interval to cool the vacuum pump.

3.5.4 Pressurization

After vacuuming the loop, the loop was pressurized to the desired supercritical pressure. Initially, the loop was directly charged with the CO₂ cylinder, which can supply pressure up to 5.8 MPa. Since this pressure is far below the supercritical pressure, the booster pump was used to further raise the loop pressure to the desired supercritical pressure. During the working of the booster pump, the hose connecting the loop inlet and the pump gets hot. That increases the temperature of the CO₂. In order to cool it, the hose was passed through a propylene glycol solution. The exhaust valves were closed during this whole process.

3.6 Test Procedure

After pressurizing, the loop was kept undisturbed for 30 minutes to equilibrate the CO₂ pressure. The outlet valves of the test section were adjusted to the predetermined position, and the LabVIEW software was used to monitor and control the experiments. The following procedure was used to perform an experiment:

1. First, all the doors of the Perspex containment were closed, and lock-key was turned ON.
2. The rectifier was turned ON and ready for use.
3. The rooftop chiller and coolant pump were turned ON.
4. 0.5 kW power was supplied to the test section by scrolling the mouse of the PC. The power was increased with the increment of 0.5 kW in 5 minutes. The desired pressure

was achieved by increasing the power as with an increase in power, pressure increases. The inlet temperature was maintained by adjusting the coolant flow rate. With an increase in power, the flow gets developed and becomes stable.

5. When the desired conditions were achieved, and flow becomes stable, data was recorded for 5 minutes.
6. After this stage, power was again increased gradually with an increment of 0.5 kW in 5 minutes till the onset of the mass flow oscillation.
7. Once the mass oscillations were observed, the power was reduced to 1 kW to suppress the oscillations and data recording was started again. The power was increased at a more gradual rate of 0.2 kW every 5 minutes to record the data for the instability boundary.

The recorded data was later analyzed to obtain the instability boundary power along with experimental system parameters.

Chapter 4 Experimental results and discussion

4.1 Introduction

This chapter presents the results of the instability experiments that were performed using two vertical parallel channel facility situated in the Energy Lab 103 in the University of Manitoba. A total of seven instability experiments are given here. The system pressure for the cases was in the range 8.25 – 9.1MPa and the inlet temperature was in the range 0.5 – 10.05 °C. For an experiment, the channel inlet temperature, system pressure, inlet and outlet channel valve openings were set. Only the input power was increased in search of the stability boundary. The input power was increased gradually in uniform steps until mass flow oscillations commenced. The power where the mass flow instability occurred was the instability threshold power. In all the cases, oscillatory flow instability was observed, and no static instability was found.

This experimental data would also be useful for those who wish to validate existing software or develop new programs. Validating codes against experimental data can further help the understanding of supercritical flow instability. The procedure to perform the experiments was already discussed in detail in Chapter 3. In this chapter, the following topics are covered:

- a) Determining the mass flow instability boundary.
- b) Instability boundary analyses.
- c) Flow behavior in channels.
- d) Channel outlet fluid and wall temperature oscillations.
- e) Mass flow oscillation period.
- f) Electrical power versus energy balance power.
- g) Estimation of uncertainty in flow instability boundary.

h) Experimental data in dimensionless form.

4.2 Determining the mass flow instability boundary

Determining the correct instability boundary is of utmost importance. Xiong et al. (2012) and Saini (2019) in their experiments had disregarded small transient oscillations and considered only self-sustained out-of-phase mass flow oscillations with evident amplitude for the instability boundary. Shisti et al. (2018a) recommended that for the flow system to be unstable, the amplitude of mass flow oscillations should be greater than $\pm 10\%$. Other numerical studies by Sharabi et al. (2008) & Xi et al. (2014a) found that there may be continuous out-of-phase mass flow oscillations at the instability boundary. They also reported that sometimes oscillation amplitude may also amplify. However, Xi et al. (2014b) in their experiments revealed that flow oscillations are not strictly continuous. For some experiments, they observed discontinuous oscillations and considered instability boundary with oscillations having more than 10 cycles.

Herein, the instability boundary was determined using the similar criteria adopted by Xiong et al. (2012) and Saini (2019). The instability boundary was determined when the mass flow rate in channels achieved self-sustained 180° out-of-phase oscillations with sudden amplitude increase. In all the cases, when evident mass flow oscillations appeared, the amplitude value was greater than $\pm 10\%$, and the oscillations were continuous in nature. Figure 4.1 shows a sample instability boundary for the system.

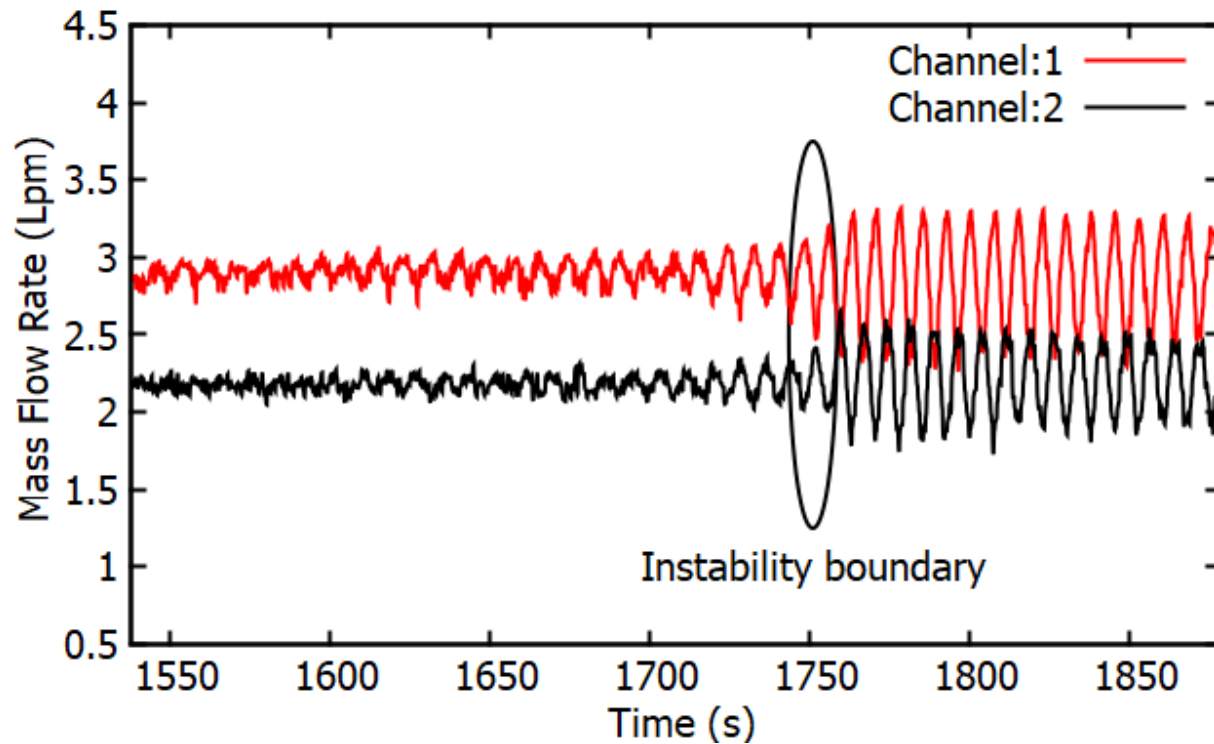


Figure 4.1: The instability boundary for the system.

4.3 Instability boundary analysis

The recorded experimental data, shown in figure 4.2, were analyzed to determine the instability boundary mass flow rate and power. The 30 sec. recorded mass flow rate data, before the commencement of the instability boundary was averaged to obtain the instability boundary mass flow rate. Averaging 30 sec. data was considered adequate. To obtain the instability boundary power (threshold power), the time around the instability boundary along with the input power to the channels was plotted, shown in figure 4.2. From the plotted experimental data, the instability boundary power was determined visually, the input power when the mass flow rate in channels oscillated out-of-phase with suddenly increased amplitude.

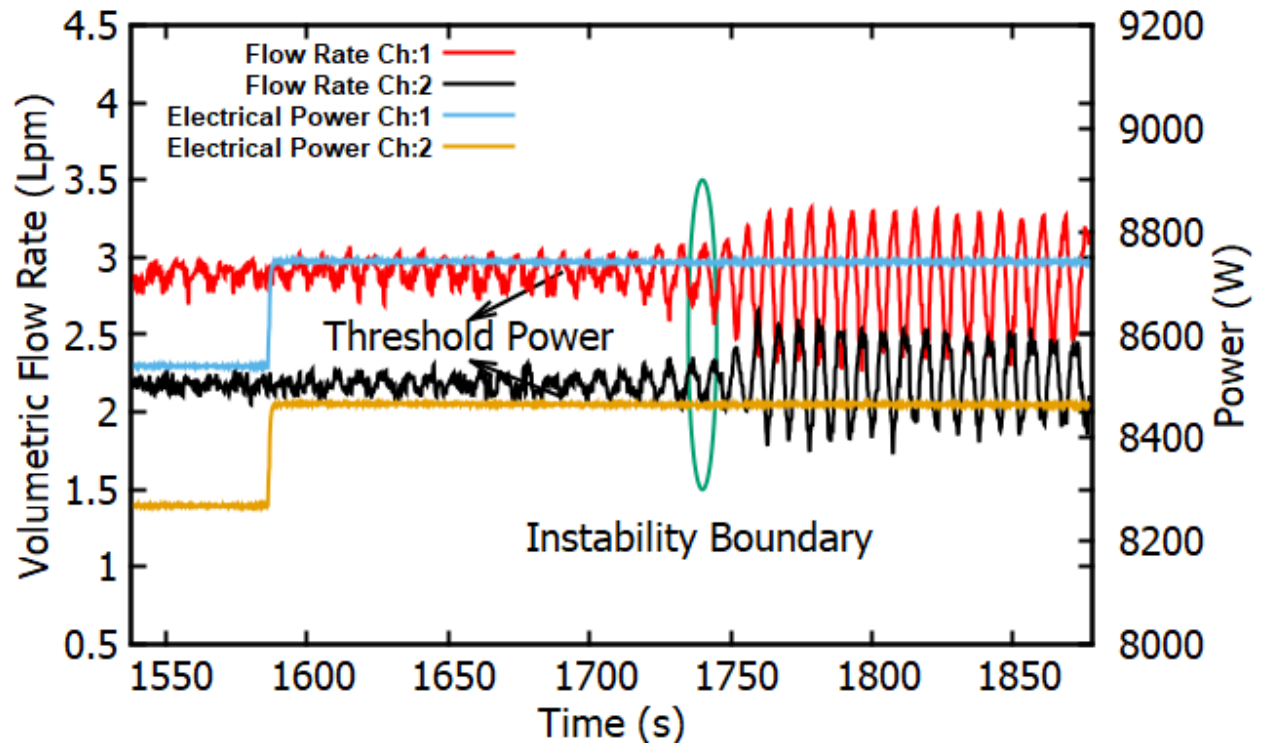


Figure 4.2: Instability boundary power.

Table 4.1 gives the system parameters at the instability boundary for the seven cases, including the mass flow rate and power. The channel inlet K -factors of both the channels for all seven experimental cases were 1.2 and 1.3, respectively. The mass flow rate given in Table 4.1 was converted from Lpm to kg s^{-1} .

Table 4.1: Parameters at the commencement of the instability boundary.

CASE	Electrical Power [kW]		Mass Flow Rate [kg s^{-1}]		Inlet Temp.	System Pressure	Outlet channel K -factor		Period of oscillation
No.	Ch1, Ch2	Total	Ch1, Ch2	Total	[$^{\circ}\text{C}$]	MPa	Channel 1	Channel 2	Second [s]
1	8.74, 8.46	17.20	0.04476, 0.03370	0.07846	6.6	9.09	3.2	23.8	7.8
2	8.25, 7.98	16.23	0.04160, 0.03445	0.07605	1.9	8.74	3.2	23.8	7.19
3	8.65, 8.37	17.02	0.04253, 0.03471	0.07724	3.5	8.97	3.2	23.8	7.2

4	8.87, 8.58	17.45	0.04286, 0.03549	0.07835	4.6	8.55	3.2	23.8	6.6
5	8.70, 8.40	17.10	0.04260, 0.03560	0.07822	5.5	8.3	3.2	23.8	6.07
6	8.80, 8.50	17.30	0.04217, 0.03442	0.07661	0.54	9.054	3.2	23.8	7.19
7	7.90, 7.60	15.50	0.03090, 0.04495	0.07585	10.05	8.25	23.8	3.2	6.1

In the above table, the oscillation period is calculated from doing a Fast Fourier Transformation (FFT) of the experimental data. This is explained in a later section.

Calculating the valve K-factors

The pressure drop across the valve was measured using the differential pressure transducer. The measured pressure-drop composed of frictional pressure-drop, gravitational pressure-drop, and local pressure-drop, and is represented in equation 4.1. Xiong et al. (2012) & Saini (2019) previously used this formula to calculate the K -factor value.

$$\Delta P_{total} = \Delta P_l + \Delta P_g + P_f \quad (4.1)$$

Where

$$\Delta P_l = \frac{K \cdot G^2}{2\rho} \quad (4.2)$$

$$\Delta P_g = \rho gh \quad (4.3)$$

$$\Delta P_f = \frac{F_r \cdot l \cdot G^2}{D \cdot 2\rho} \quad (4.4)$$

ΔP_{total} is obtained from the differential pressure transducer reading. By substituting the value of ΔP_{total} , ΔP_l , ΔP_g , and ΔP_f in equation 4.1, the value of K can be calculated.

4.4 Case Study (Case 1)

The case 1 was performed at the inlet temperature 6.6 °C and system pressure 9.09 MPa. The inlet valves were fully opened, and the outlet valve for channel 1 was closed at approximately 30° and for channel 2 at approximately 45° from the fully opened position. The threshold power for channels 1 & 2 was calculated 8.74 kW and 8.46 kW with an instability boundary mass flow rate of 0.04476 and 0.03370 kg s⁻¹. The findings of the case 1 are discussed below. (For all other cases, the findings were similar.)

4.4.1 Flow behavior in channels

The flow rate in the channels got distributed with the input power increment and is divided into three stages, as follows:

- a) **Stage I** – Initially at a low input power, the flow rate in the channels was almost equal, figure 4.3. Here, the channel outlet fluid temperature for both the channels was below the pseudo-critical temperature.
- b) **Stage II** – With an increase in input power, the flow rate got distributed in channels and become asymmetric, figure 4.4. Here, the channel outlet fluid temperature for both the channels was in the vicinity of the pseudo-critical temperature.
- c) **Stage III** – With further increase in input power, the flow rate started oscillating 180 ° out-of-phase and instability boundary was determined, figures 4.5 and 4.6. Here, the channel outlet fluid temperature, for both the channels, was beyond the pseudo-critical temperature.

A similar type of flow distribution was already reported for water (Xiong et al., 2012) but there the flow rate oscillated irregularly before oscillating 180° out-of-phase.

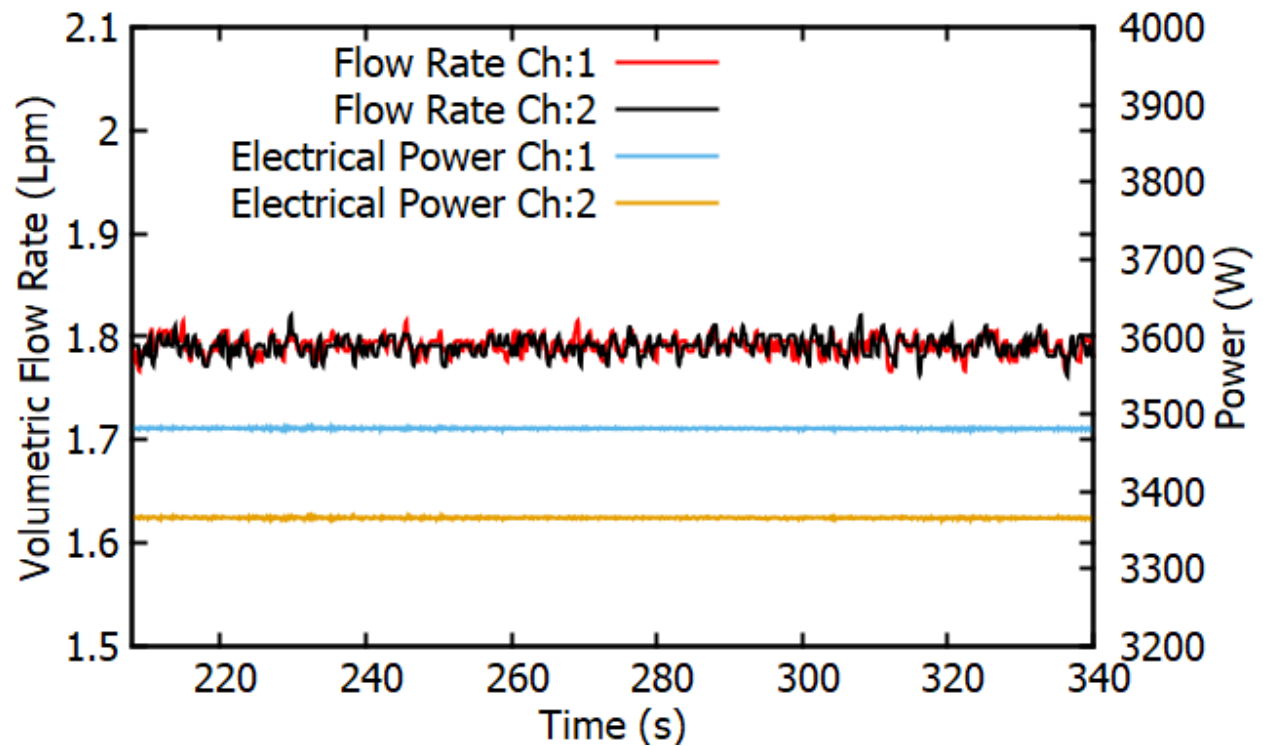


Figure 4.3: Almost symmetrical flows between the channels at low input power (Case 1).

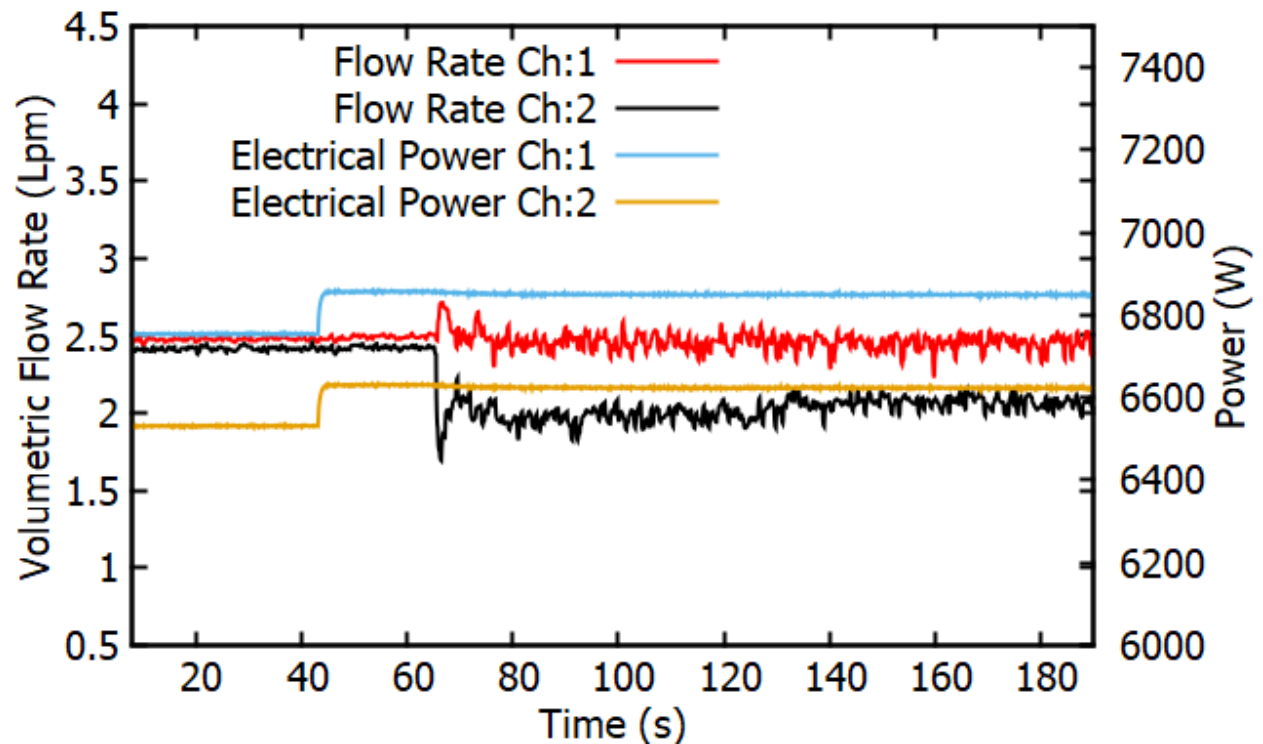


Figure 4.4: Non-symmetric flows between the channels with input power increase (Case 1).

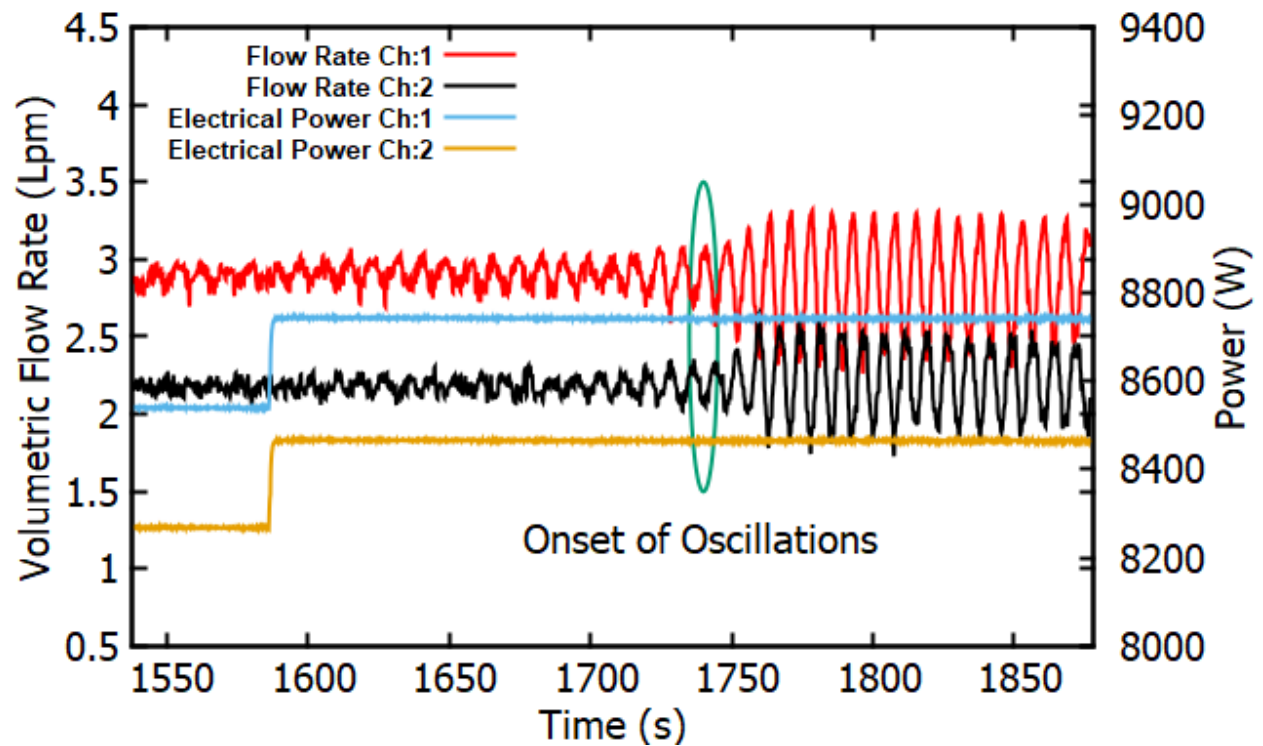


Figure 4.5: The onset of the flow oscillations with input power increase (Case1).

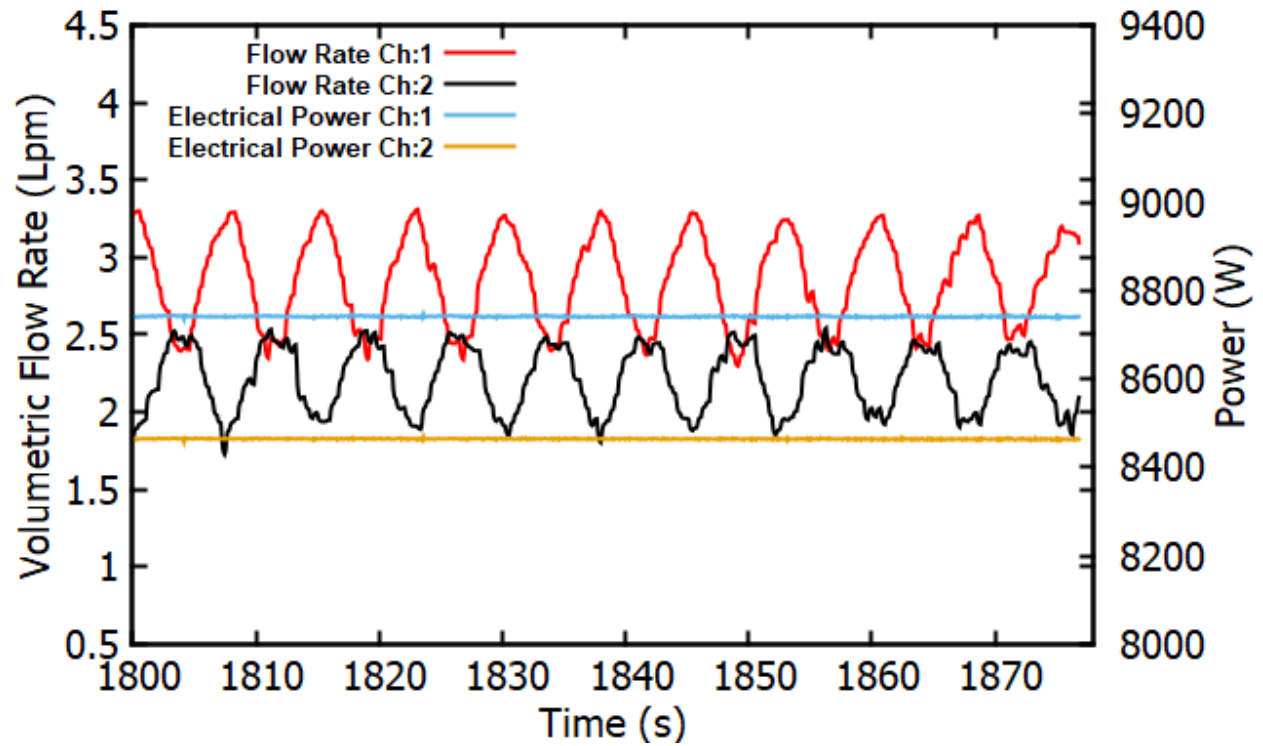


Figure 4.6: Flow oscillations at instability boundary (Case1).

4.4.2 Channel outlet fluid and wall temperature oscillations

It was obvious that once the mass flow oscillations started, the channel outlet fluid and wall temperatures would also oscillate. The channel outlet fluid and wall temperatures oscillated out-of-phase at the same frequency as that of mass flow rate, as expected. The normalized plots were drawn by dividing interval data at each time step with the mean rate data. These plots were drawn to check whether the mass flow and temperature oscillations were perfectly 180° out-of-phase or not. Figures 4.7- 4.9 show the normalized plot for mass flow rate, channel outlet fluid temperature, and channel outlet wall temperature oscillations. From figures 4.8 and 4.9, the channel outlet fluid and wall temperature oscillations (especially the channel outlet wall temperature oscillations) were not perfectly 180° out-of-phase as compared to the mass flow oscillations, figure 4.7. This was because of the larger time response of the thermocouples compared to the response time of the flow meter. The response time of the wall temperature thermocouples was even larger than the response time of the fluid temperature thermocouples.

The channel outlet fluid temperature oscillations were also reported for water (Xi et al., 2014b). There the channel outlet fluid temperature oscillations oscillated with the same frequency as the mass flow oscillations.

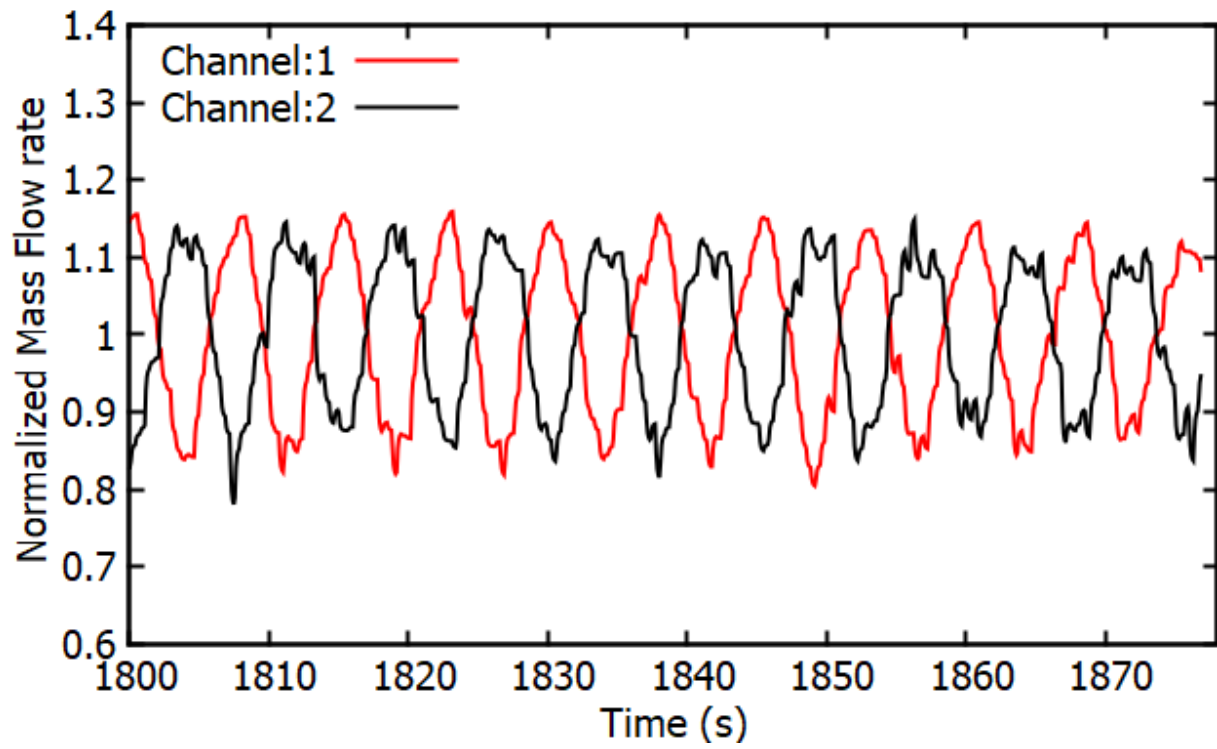


Figure 4.7: Normalized mass flow rate oscillations.

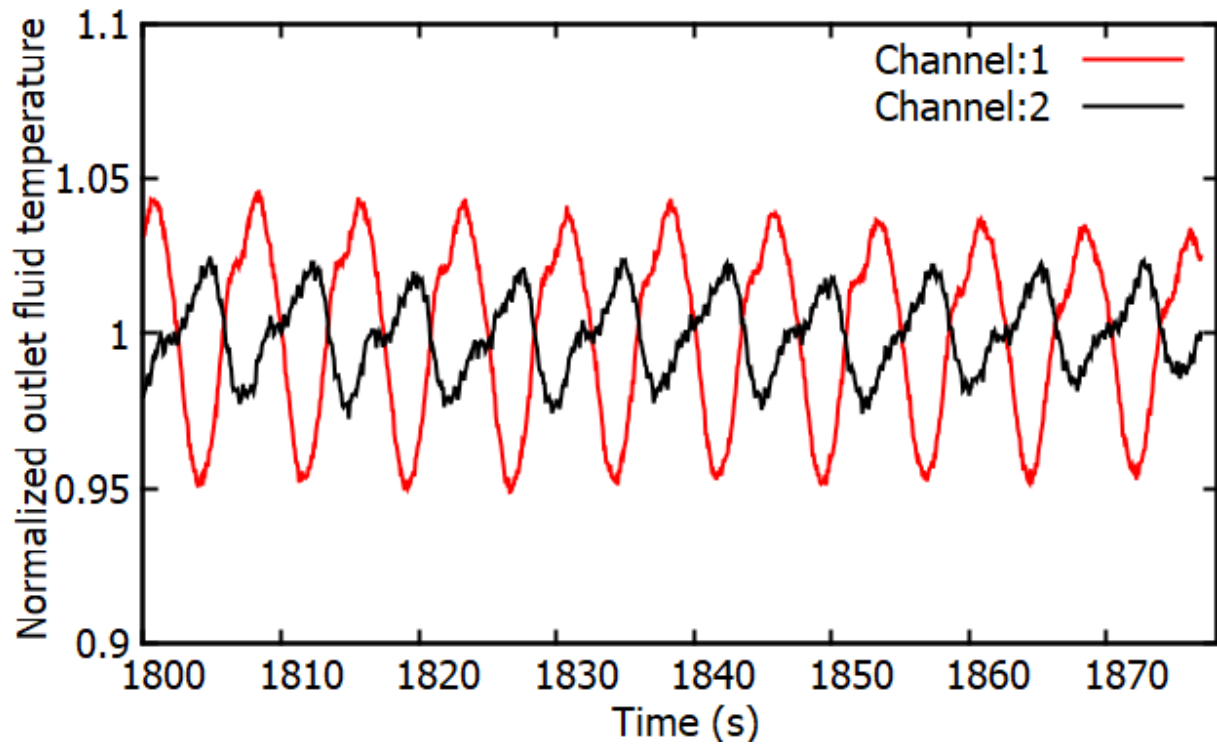


Figure 4.8: Normalized channel outlet fluid temperature oscillations.

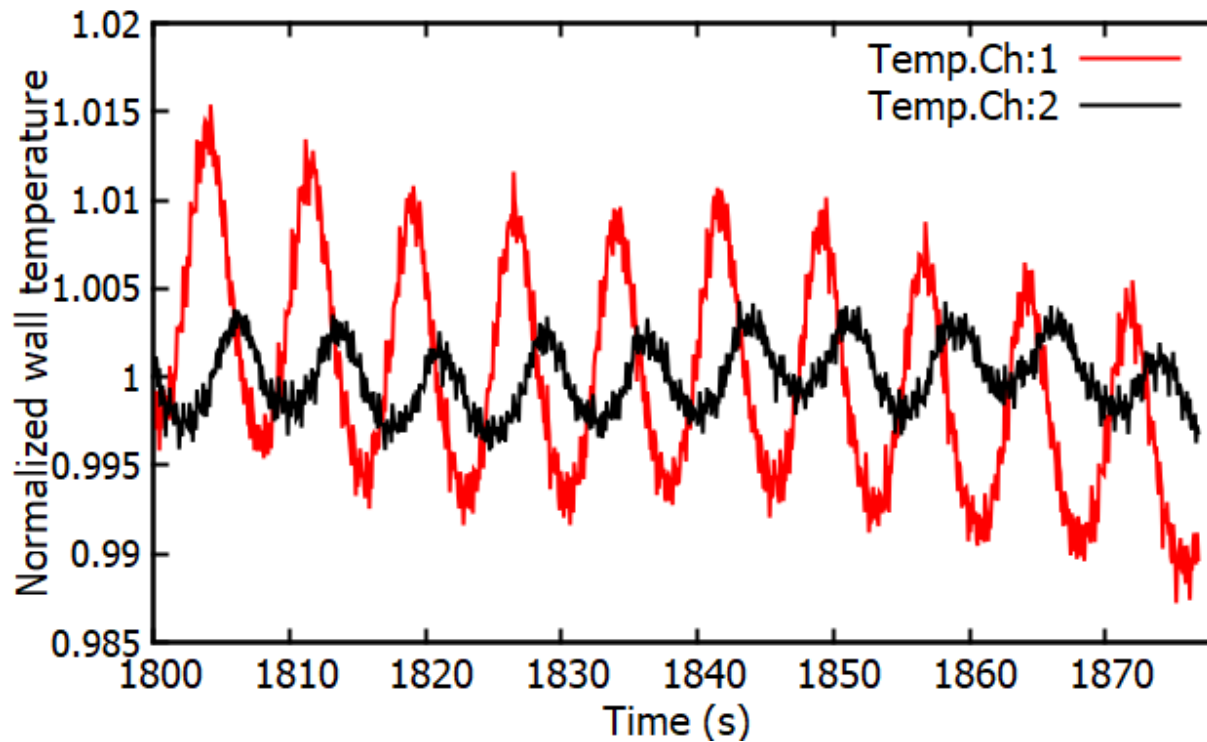


Figure 4.9: Normalized channel outlet wall temperature oscillations.

4.4.3 Oscillation Period

The correct prediction of the oscillation period along with the instability boundary power is paramount to determining a numerical model accuracy and reliability for engineering use. Fast Fourier Transformation (FFT) of the flow-meter data is believed to be an accurate way of determining the experimental oscillation period. An FFT analysis provides information on all frequencies not obvious to the naked eye, and the uncertainty in the oscillation period obtained by an FFT analysis is expected to be substantially small. Ghadge (2018) used it successfully for experimental and CFD results and revealed the various hidden frequencies. Saini et al. (2020) also applied FFT analyses to calculate the oscillation period.

In FFT analyses the time domain signal, which is a series of real numbers, is converted into the frequency domain as a series of complex numbers. The amplitude for the signal is calculated

from the magnitude value of the complex number, and the phase shift for the signal is calculated from the angle between the real and imaginary parts of the complex number. This analysis untangles the original signal into all major and minor signals that contributed to the original signal. The frequency of each signal (major and minors) is represented in an FFT plot. The oscillation period can be determined by taking the inverse of the frequency. This was done for all the seven experimental cases.

For Case 1, figures 4.10 and 4.11 show the amplitude plot of FFT for channels 1 and 2. They give only the major oscillation period of 7.8 sec. The phase between the oscillations was checked by plotting the phase shift plot of the FFT, shown in figure 4.12. Evident from figures 4.10, 4.11 and 4.12, the frequency corresponding to the maximum amplitude where the phase crosses over, out of phase.

When the oscillation period of the author's experimental cases was compared with the oscillation periods of Saini cases (2019); it was found that the oscillation periods of Saini's cases were much smaller. Saini reported an oscillation period between 1–3.4 sec., whereas the author's cases were between 6.1–7.8 sec. The reason for the different oscillation periods is believed because of different fluid velocity in channels. For Saini's cases, the total mass flow rate was higher. Higher the fluid velocity, shorter will be the fluid transit time, and smaller will be the oscillation period. For the author's cases, the total mass flow rate was low. Hence, lower the fluid velocity, longer will be fluid transit time, and larger will be the oscillation period.

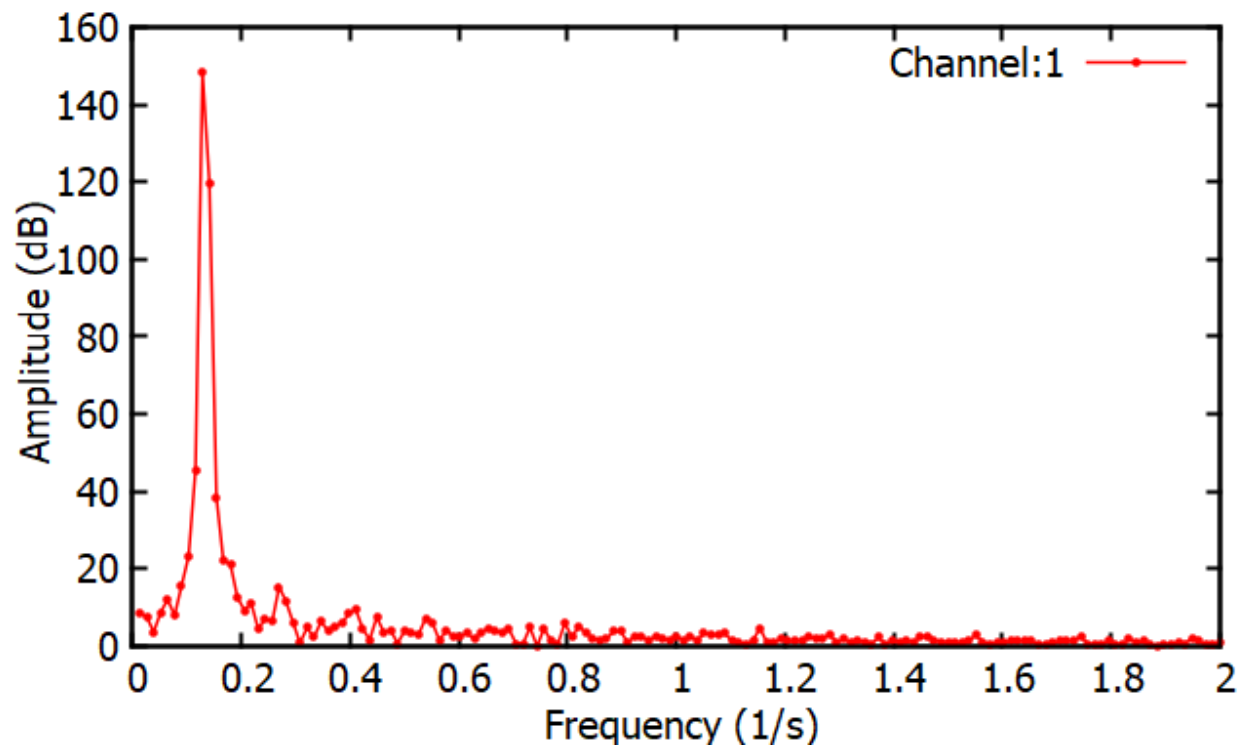


Figure 4.10: Amplitude plot of FFT of channel 1 (case 1).

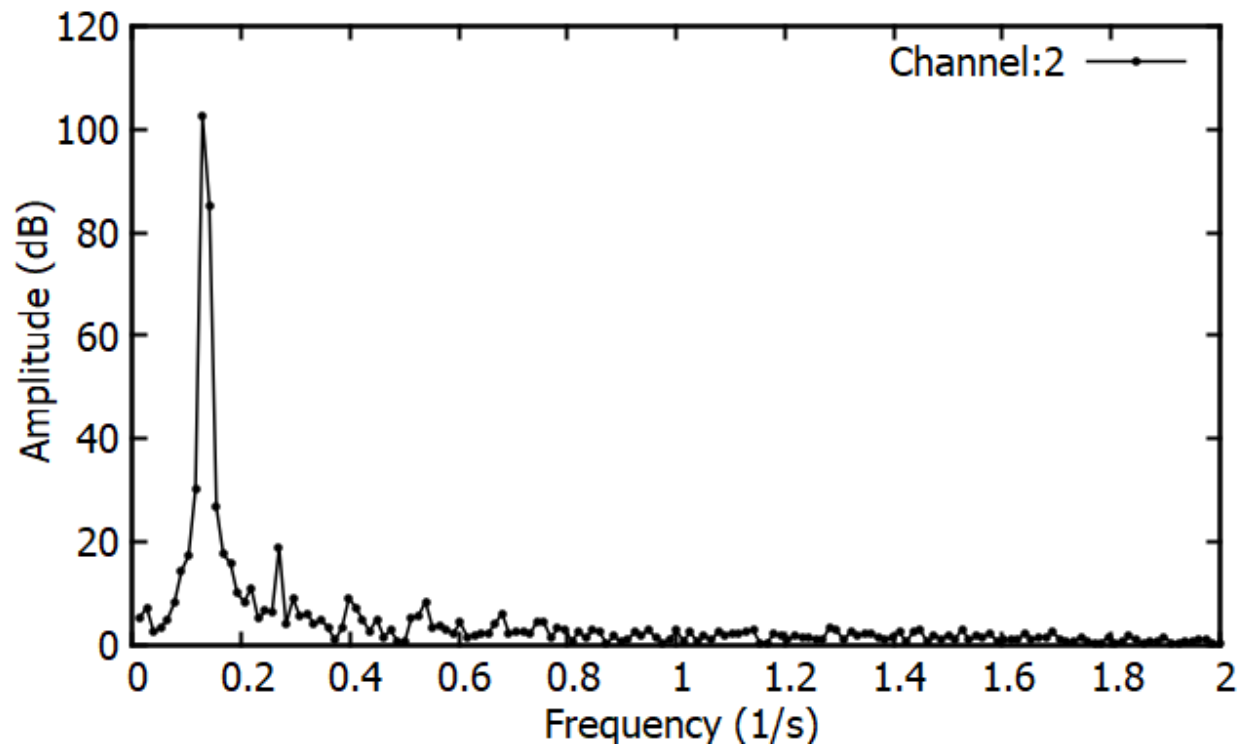


Figure 4.11: Amplitude plot of FFT of channel 2 (case 1).

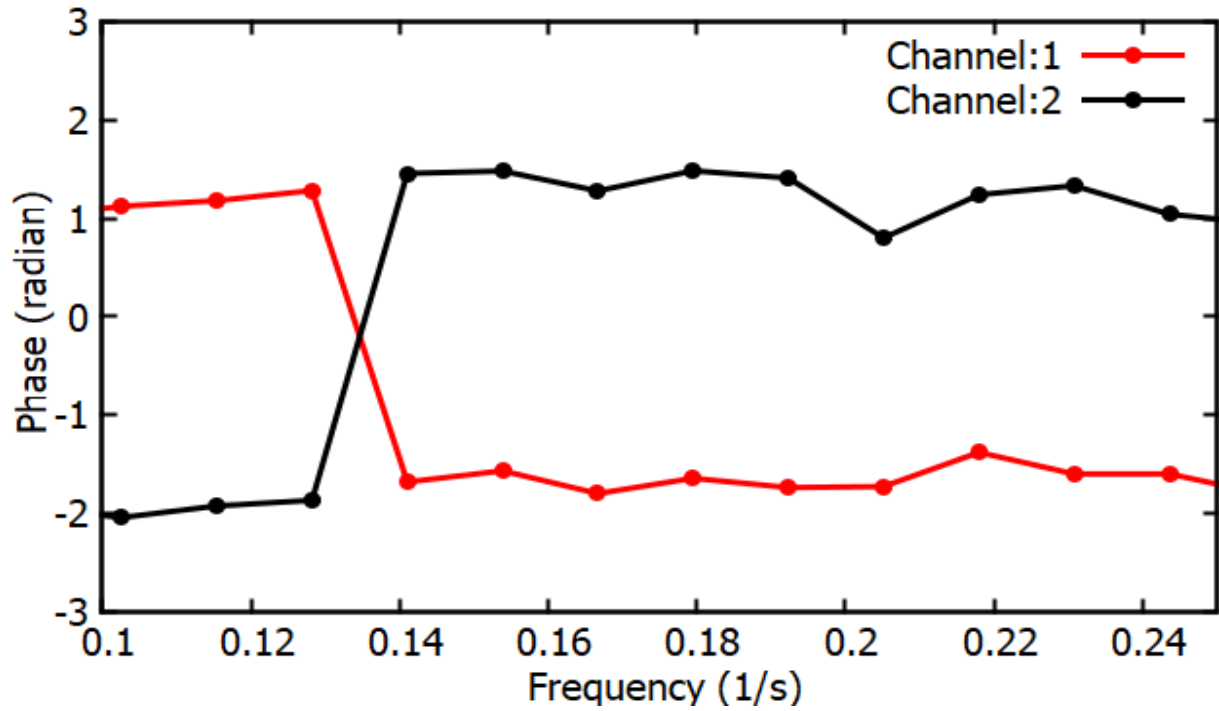


Figure 4.12: Phase plot of the FFT (case 1).

4.5 Oscillation period vs. fluid transit time

For two-phase flow instability Kakac and Bon (2008) reported that the mass flow oscillation period is between one to two times the fluid transit time through the channel. To determine if this is also true for supercritical flow instability, it was decided to calculate the actual fluid transit time in the channels. Figure 4.13 gives a plot of Ratio of Oscillation Period to Transit Time for all seven experimental cases. The plot shows that the oscillation period is, indeed, between one to two times the fluid transit time through the channel. Thus, the belief is confirmed. The transit time of fluid through the channel was calculated by integrating the fluid time at each node along the channel. The flow velocity at each node was obtained from the steady-state solution using SPORTS steady-state program (Chatoorgoon, 1986).

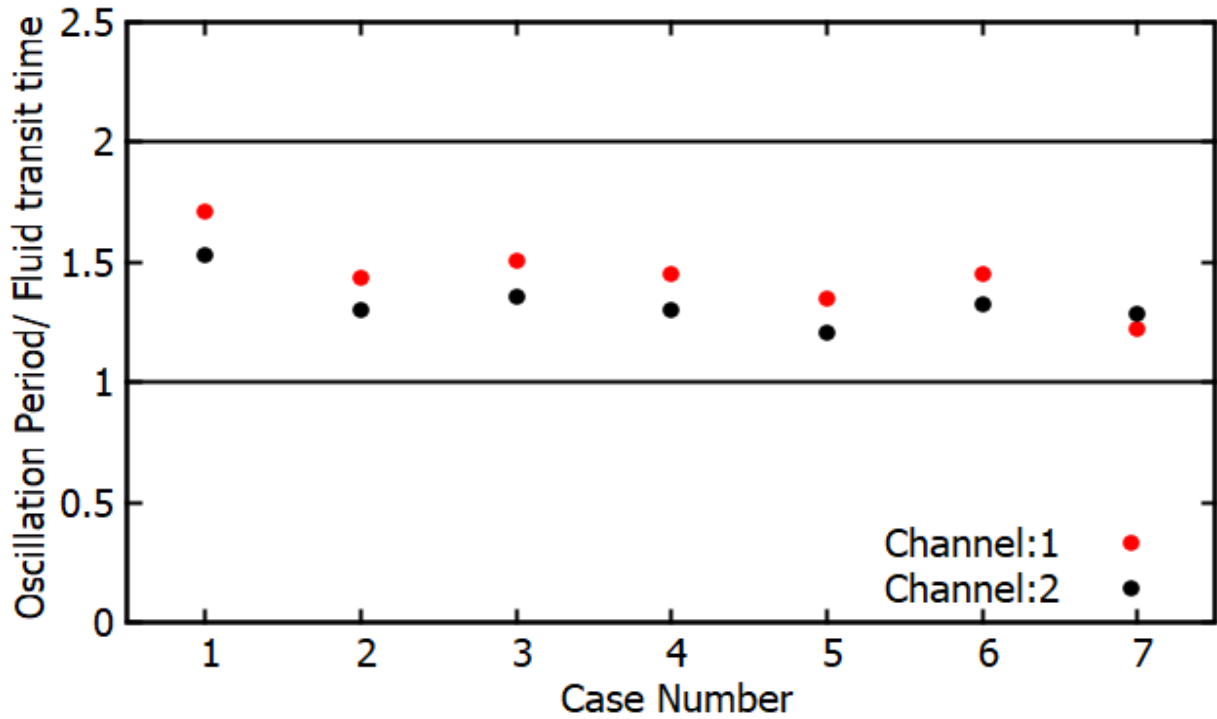


Figure 4.13: Period of oscillation to transit time for all seven experimental cases.

4.6 Electrical power vs. energy balance power

The electrical power that was supplied to the channels to heat the fluid was calculated using the formula in equation (4.5).

$$P = \frac{V^2}{R} \quad (4.5)$$

Where P is electrical power in watt (W), V is voltage drop (V) and R is electrical resistance of test section channel in ohm (Ω).

The energy balance power (EB power) required to heat the fluid was calculated from the general formula obtained from first law of thermodynamics (energy balance equation) in equation (4.6).

$$Q = m \cdot (h_{out} - h_{in}) \quad (4.6)$$

Where Q represents energy balance power in watt, m represents mass flow rate ($\text{kg} \cdot \text{s}^{-1}$) and h_{out} and h_{in} represent fluid enthalpies at the outlet and inlet of channels (J/kg/s). Figure 4.14 shows

the comparison of the electrical and energy balance powers and figure 4.15 shows the percentage difference between the electrical and energy balance powers. It is evident that there exists a small percentage difference, between 2-3%, between electrical and energy balance powers. This small discrepancy is attributed to the heat losses to the surroundings.

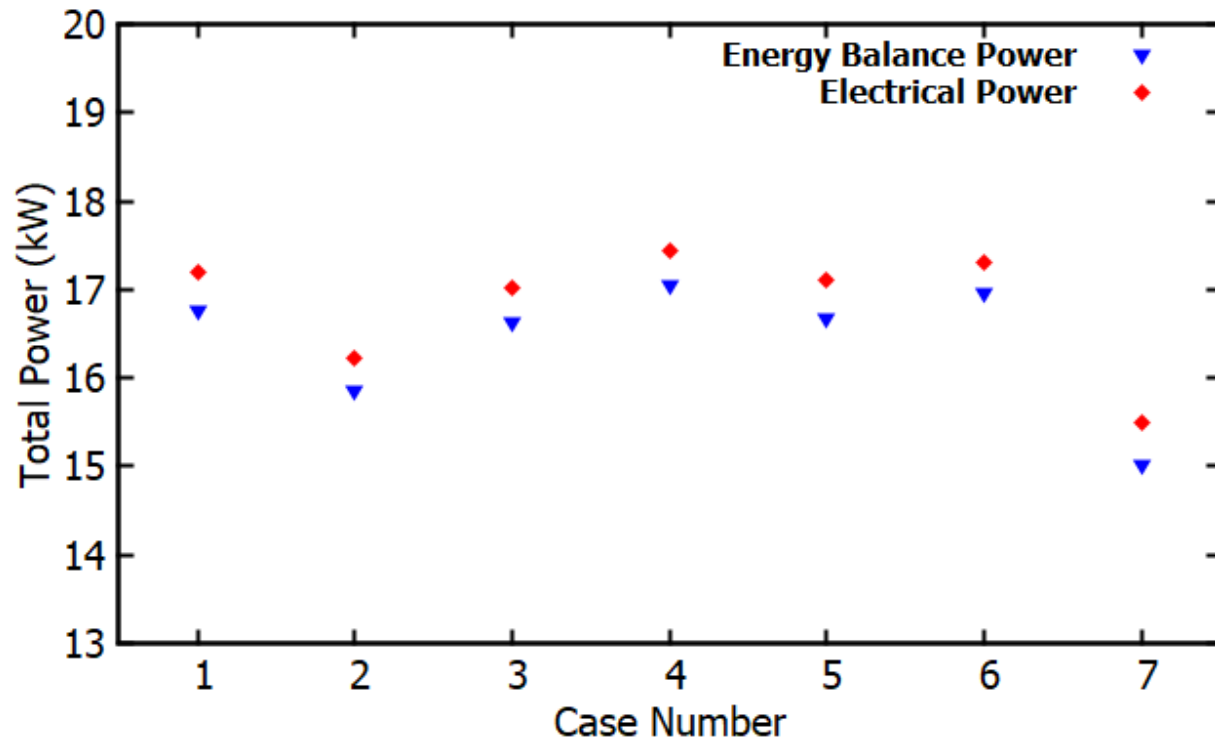


Figure 4.14: Comparison of electrical and energy balance powers.

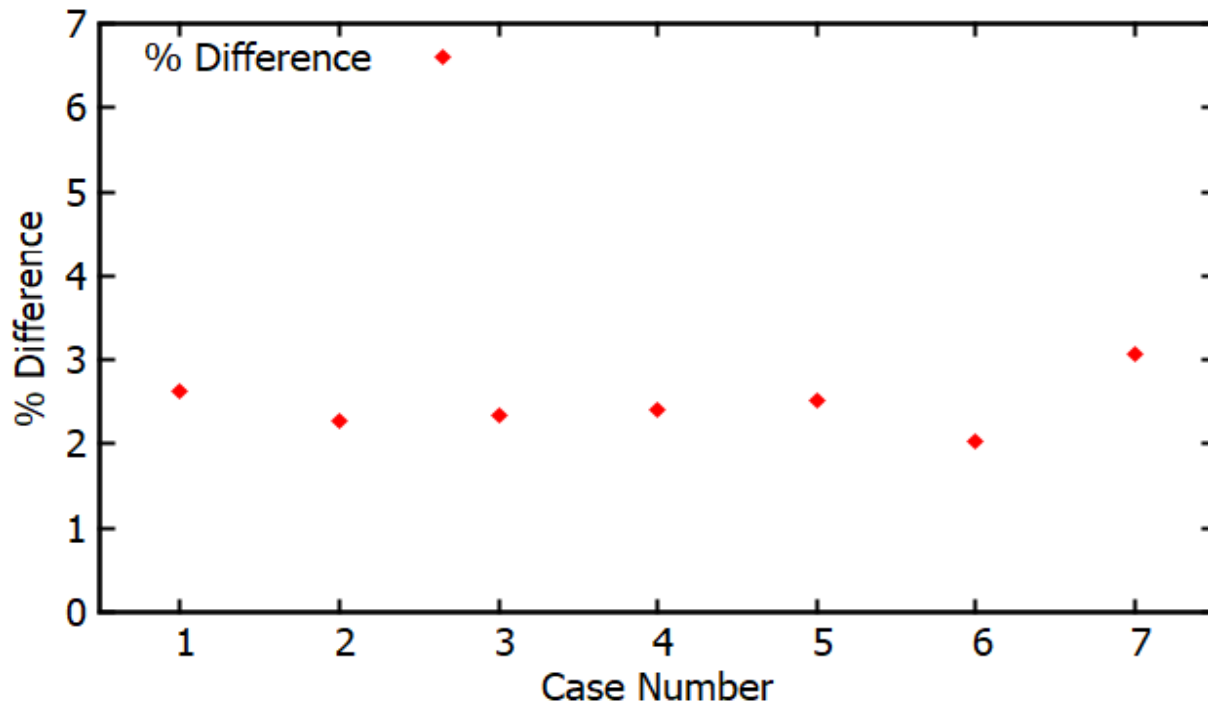


Figure 4.15: Percentage difference between electrical and energy balance powers.

4.7 Estimation of uncertainty in instability boundary

An attempt here is made to give a rough estimate of uncertainty in the experimental flow instability boundary. Both type A and type B uncertainties were considered while estimating the uncertainty for flow instability boundary. Type A uncertainty corresponds to the statistical analysis of measured data which primarily includes random errors. Type B uncertainty corresponds to the evaluation of uncertainty by means other than the statistical analysis. This includes systematic errors and other uncertainty that are believed to be important by the experimenter. Here, for type B uncertainty, uncertainties related to instruments are considered.

Table 4.2 gives the details of the uncertainties of various measurements calculated through statistical analysis of recorded data. The formula to calculate Standard error is expressed in equation 4.7.

$$\sigma_e = \frac{sd}{\sqrt{N}} \quad (4.7)$$

Where σ_e is standard error (Type A uncertainty), sd is standard deviation and N is number of measurements.

Table 4.2. Type A uncertainty calculated from statistical analysis of measured data.

Parameter	Standard Error/Type A Uncertainty
Mass flow rate	$\pm 0.4 \%$
Fluid temperature	$\pm 0.3 \%$
System pressure	$\pm 0.03 \%$
Pressure-drop	$\pm 1.0 \%$

As mentioned earlier, instrumental uncertainties are considered for type B uncertainties. Details of instrumental uncertainties are already provided in the Experimental setup section, chapter 3 in Table 3.3. Both Type A and Type B uncertainties are combined using law of propagation of uncertainties commonly known as “root-sum-of-squares” or “RSS” method to get a combined uncertainty for individual parameter, (UNC Physics Lab Manual Uncertainty Guide). The formula for “RSS” method is described in equation 4.8, and combined uncertainty for different parameters is presented in Table 4.3.

$$U = \pm\sqrt{(U_a)^2 + (U_b)^2} \quad (4.8)$$

Where U is combined uncertainty, U_a is Type A uncertainty (which is σ_e) and U_b is Type B uncertainty (Instrument uncertainty).

Table 4.3. Combined uncertainties of different parameters.

Parameter	Combined Uncertainty (<i>U</i>)
Mass flow rate	± 3.02 %
Fluid temperature	± 0.6 %
System Pressure	± 0.5 %
Pressure-drop	± 4.1 %

Since in an experiment, channel flow instability boundary is governed by system pressure, inlet temperature, mass flow rate, and pressure drop across the valves. If the channel inlet pressure drop is increased, the stability boundary increases, and if the channel outlet pressure drop is increased, the stability boundary decreases. With an increase in system pressure or channel mass flow rate, the stability boundary increases. With an increase in channel inlet temperature, the stability boundary decreases up to a certain point and, thereafter, starts increasing. Since the system pressure, inlet temperature, mass flow rate and pressure-drop have a direct impact on the channel flow instability boundary; the uncertainty in flow instability boundary comprises the uncertainties related to these parameters and is calculated using “root-sum-squares” and “RSS” method discussed earlier. The formula for overall uncertainty for flow stability boundary using “RSS” is described in equation 4.9.

$$U_b = \pm \sqrt{U_m^2 + U_f^2 + U_p^2 + U_{pd}^2} \quad (4.9)$$

$$U_b = \pm \sqrt{3.02^2 + 0.6^2 + 0.5^2 + 4.1^2} = \pm 5.2 \% \quad (4.10)$$

Where U_b is uncertainty in flow instability boundary, U_m combined uncertainty in mass flow rate, U_f combined uncertainty in fluid temperature, U_p combined uncertainty in system pressure and U_{pd} combined uncertainty in pressure-drop, all given in Table 4.3. The calculation of combined uncertainty using “RSS” method is equivalent to the standard deviation of the result, making the uncertainty value correspond with a 68 % confidence interval. If a wider confidence interval is required, the uncertainty value is multiplied by coverage factor k (usually 2 or 3) to provide an uncertainty range that is believed to include true value with a confidence of 95 % (for $k = 2$) or 99.7 % (for $k = 3$), (UNC Physics Lab Manual Uncertainty Guide). Usually, 95 % confidence level has been found convenient for conducting scientific research and is universally used. Therefore, the uncertainty value of flow instability boundary obtained in equation 4.11 is multiplied by factor $k = 2$ to obtain the overall uncertainty in flow instability boundary with a confidence level of 95 %.

$$U_{ob} = \pm (U_b * k) \quad (4.11)$$

$$U_{ob} = \pm (5.2 * 2) = \pm 10.4 \% \quad (4.12)$$

Where U_{ob} is overall uncertainty in flow instability boundary with confidence level of 95 %.

4.8 Experimental results in dimensionless form

Because engineering systems like nuclear reactors would invariably use supercritical water as the working fluid, water data is most relevant. Initially, the UM loop was designed for water, but University personnel became fearful of the high temperatures and pressures involved. That left us no option but to use CO₂ instead. Some researchers proposed dimensionless parameters that may be able to convert the CO₂ instability boundary data to H₂O instability boundary data. Herein, the dimensionless parameters proposed by Ambrosini and Sharabi (2008) are used to

represent the CO₂ instability boundary data in dimensionless form. These parameters were opted because of their popularity among researchers.

These parameters were derived for supercritical flow in general and should also be valid for supercritical flow instability data. These parameters reduce the number of variables considered for the flow stability analysis to just two numbers known as sub-pseudo-critical number and trans-pseudo-critical number. The sub-pseudo-critical number corresponds to the effect of channel inlet temperature, and the trans-pseudo-critical number corresponds to the effect of system mass flow rate and power. The dimensionless numbers for a given geometry and given set of K factors, for supercritical flow are:

$$N_{spc} = \frac{\beta_{pc}}{C_{p,pc}} (h_{pc} - h_{in}) \quad (4.13)$$

$$N_{tpc} = \frac{P}{m} \frac{\beta_{pc}}{C_{p,pc}} \quad (4.14)$$

Where: N_{spc} is the sub-pseudo-critical number, N_{tpc} is the trans-pseudo-critical number, β_{pc} represents the isobaric thermal expansion coefficient [K⁻¹] corresponding to pseudo-critical point, $C_{p,pc}$ represents the specific heat at constant pressure corresponding to pseudo-critical point [kJ kg⁻¹ K⁻¹], h_{pc} represents the specific enthalpy of fluid at pseudo-critical point [kJ kg⁻¹], h_{in} represents the specific enthalpy of fluid at the inlet [kJ kg⁻¹], P represents the power [kW] and m represents the mass flow rate [kg s⁻¹].

The supercritical CO₂ flow instability data of the seven experimental cases were converted into the dimensionless form and is presented in table 4.4. The values of β_{pc} , $C_{p,pc}$, h_{pc} , and h_{in} were obtained using NIST property package. This data would be useful for modeling water in the

same loop with a given set of K - factor. Later, in the numerical results section, the accuracy of these parameters to accurately convert the flow instability data of CO_2 to H_2O is discussed.

Table 4.4: Experimental data in dimensionless form.

Case No.	N_{spc}	N_{tpc}
1.	1.023	1.680
2.	1.125	1.686
3.	1.084	1.706
4.	1.085	1.790
5.	1.082	1.780
6.	1.130	1.735
7.	0.993	1.646

Chapter 5 Numerical results and discussion

5.1 Introduction

The results obtained from the instability experiments (current and Saini's experiments) were analyzed using a 1-D linear in-house program. The first version of this program was developed in 2005 by Chatoorgoon. At that time, it was developed only for a single-channel flow. Later, in 2018, Chatoorgoon and Ghadge extended this linear program to two and three parallel channel flow, including the wall-heat storage effect. At the time of development, the program was only used for supercritical water. It performed very well against the water data. Herein, the credibility of the program to predict supercritical CO₂ flow instability in two parallel channels is assessed. Validating the program for multiple fluids would make it suitable for extended engineering use and further help the understanding of supercritical flow instability in various geometries and configurations.

5.2 Linear Program

The Linear program is based on linear perturbation theory and the frequency domain solution. The time-domain governing equations (mass, momentum, and energy) were linearized about the steady-state solution by applying a small perturbation. The initial steady-state solution was obtained from SPORTS code, complete details are described in (Chatoorgoon,1986), and are not repeated here. The time-domain governing equations were then transformed to the frequency-domain by taking the Laplace transform. A transfer function was derived. The stability of the system was determined using the Nyquist plot. The oscillation period was calculated at the cross-

over frequency of the Nyquist plot. The solution to this method is exact in space and time and is much less time-consuming than a non-linear solution. However, it does not predict the limit cycle and the amplitude of oscillations and ignores non-linear effects.

The lumped parameter wall model that ignores the variation of wall temperature in the radial direction was used. In addition, axial conduction in the wall was also ignored. This was the simplest approach to study wall-heat storage effect and is commonly used among researchers. The convective heat transfer coefficient was determined from the supercritical Dittus-Boelter correlation. Complete details are given in Ghadge et al. (2020) and are not repeated here.

Assumptions Made

- a) The 1-D governing conservation equations are used.

Boundary Conditions

- a) Inlet – The Laplacian of the total pressure perturbation and density perturbation is given as zero. A small perturbation is given to the inlet velocity of channels.
- b) Outlet – The Laplacian of each channel total pressure perturbation is specified to be equal.
- c) Walls – Heating power is specified. The Laplacian of wall and fluid temperature perturbation were given zero.

The author's experimental results and Saini's experimental results were used to assess the performance of the 1-D linear program to predict the supercritical CO₂ instability data. Instability boundary predictions were produced without and with wall-heat storage.

5.3 Sensitivity test of heat-transfer coefficient

Ghadge et al. (2020) selected the Dittus-Boelter correlation for the convective heat-transfer coefficient determination. The Dittus-Boelter correlation is given in equation 5.1. They found that when using supercritical Dittus-Boelter correlation for two parallel channels, the results become close to the experiment data; however, the effect was substantially small. The RMS error for Xiong et al. (2012) cases with regular Dittus-Boelter correlation was 2.16% and with supercritical Dittus-Boelter correlation was 1.75%. When the supercritical Dittus-Boelter correlation was doubled and halved, the results did not differ significantly. For Xiong et al. case 1, the boundary power using original supercritical Dittus-Boelter correlation was 68.9 kW. When the correlation was halved, boundary power increased to 72.2 kW, and when doubled, it reduced to 66.7 kW. They concluded that there was small effect of heat transfer coefficient for two parallel channel instability, and results were not only subjected to experimental uncertainties, but also to uncertainties in heat-transfer coefficient. In addition, they also found that when modeling two identical parallel channels, the effect of wall-heat storage perfectly cancelled out irrespective of change in value of heat-transfer coefficient. When the value of heat-transfer coefficient was halved and doubled for two identical parallel channels, the boundary power was same as the no wall-heat boundary power. In their study, they used supercritical Dittus-Boelter correlation for determination of heat-transfer coefficient. From Ghadge et al. (2020) study, it is evident that because of cancellation effect between the two parallel channels, the wall-heat storage results are not much sensitive to the change in value of heat-transfer coefficient. Since the cancellation effect between the two channels also exists in the present study; discussed in later section. Therefore, similar results to Ghadge et al. were expected.

$$Nu_b = C_{DB} Re_b^{0.8} Pr_b^{0.4} \quad (5.1)$$

Where C_{DB} is 0.023 for regular fluids (sub-critical fluids) and 0.0243 for supercritical fluids.

Author's Case 2 was selected for the sensitivity study of the heat transfer coefficient. Table 5.1 gives the details of the experimental and numerical threshold powers for case 2. The % error between experimental and numerical threshold power when using regular Dittus-Boelter correlation was 1.0% and when using supercritical Dittus-Boelter correlation was 0.8%. In addition, when the supercritical Dittus-Boelter correlation was halved, the threshold power increased to 16.58 kW and when it was doubled, the threshold power reduced to 16.05 kW. It is evident that the results changes when changing the heat-transfer coefficient; however, the effect is substantially small, and can be ignored. This mimic the previous finding of Ghadge et al. (2020) done with water. It is also evident that presented results are not only subjected to the uncertainties of experiments, but the uncertainties related to heat-transfer coefficient also. For all the cases, the supercritical heat-transfer correlation was used for heat-transfer coefficient determination.

Table 5.1: Threshold powers for author's case 2.

Experimental Threshold power (Electrical Power)	Threshold Power (Without heat-wall storage effect)	Threshold Power (Regular Dittus- Boelter correlation)	Threshold Power (Supercritical Dittus- Boelter correlation)
16.23 kW	16.0 kW	16.4 kW	16.1 kW

5.4 Linear results of experimental cases

5.4.1 Mass flow rate split in the channels

Before predicting the threshold power for the system, it is of utmost importance that the code splits the total mass flow rate in the channels approximately the same as the experimental mass flow rate in the channels. To determine the mass flow rate split in channels, the experimental geometry, total mass flow rate, system pressure, channel inlet temperature, inlet and outlet K -factors and the power ratio were specified to the code input data file to produce a steady-state solution. The channels mass flow rate split was checked from the output file of the steady-state run. Tables 5.2-5.3 gives the details of the mass flow rate split experimentally and the mass flow rate split obtained by the code for the author's cases and Saini's cases. For the author's cases, the RMS error between the code predicted mass flow rate split and experimental mass flow rate split was 0.92 %, for channel 1, and 1.03 %, for channel 2. For Saini's cases, the code predicted the mass flow rate split with an RMS error of 1.09 %, for channel 1, and 0.91 % for channel 2. These results are reasonable.

Table 5.2: Comparison of the mass flow rate split experimentally and the mass flow rate split predicted by the code for the author's cases.

Case number	Experimental Mass flow rate [kg/s]		Predicted mass flow rate [kg/s]	
	Ch1	Ch2	Ch1	Ch2
1.)	0.04476	0.03370	0.04430	0.03416
2.)	0.04160	0.03445	0.04141	0.03464
3.)	0.04253	0.03471	0.04234	0.03490
4.)	0.04286	0.03549	0.04247	0.03588
5.)	0.04260	0.03560	0.04223	0.03597
6.)	0.04217	0.03442	0.04169	0.03490

7.)	0.03090	0.04495	0.03130	0.04455
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Table 5.3: Comparison of the mass flow rate split experimentally, and the mass flow rate split predicted by the code for Saini's cases.

Case number	Experimental mass flow rate [kg/s]		Predicted mass flow rate [kg/s]	
	Ch1	Ch2	Ch1	Ch2
1.)	0.0473	0.0465	0.0470	0.0468
2.)	0.0347	0.0291	0.0342	0.0295
3.)	0.0661	0.0566	0.0654	0.0574
4.)	0.0578	0.0534	0.0572	0.0540
5.)	0.0356	0.0563	0.0359	0.0560
6.)	0.0374	0.0590	0.0379	0.0584
7.)	0.0378	0.0610	0.0381	0.0607
8.)	0.0357	0.0598	0.0361	0.0593
9.)	0.0584	0.0561	0.0589	0.0556
10.)	0.0395	0.0609	0.0402	0.0602
11.)	0.0483	0.0469	0.0482	0.0470
12.)	0.0526	0.0514	0.0523	0.0517
13.)	0.0427	0.0522	0.0431	0.0519
14.)	0.0440	0.0562	0.0444	0.0558
15.)	0.0472	0.0612	0.0479	0.0605

5.4.2 Threshold power

Since the 1-D linear program can model the wall-heat storage effect, the instability threshold power was produced without and with wall-heat storage. First, the steady-state run was obtained

by specifying experimental geometry, total mass flow rate, system pressure, channel inlet temperature, inlet and outlet K -factors, and the power ratio to the code input file. This steady state was used by the linear program to determine the instability threshold power for the system. The applied power was varied until the system became unstable. The power where the system became unstable was the threshold power for the system. The system was considered unstable when the contour on the Nyquist plot encircles $-1,0$. Figure 5.1 shows the Nyquist plot at the instability boundary for the author's case 1, without wall-heat storage effect. The instability threshold power was obtained for all experimental cases of the author and Saini. Figures 5.2 and 5.3 show the comparison of energy balance power, electrical power, and numerical power at the stability boundary without and with wall-heat storage effect for the author's and Saini's experimental cases. The energy balance power for the first experimental case of Saini, shown in figure 5.3, was believed to be inaccurate as the outlet channel fluid temperature was near the pseudo-critical temperature. Hence, the channel outlet temperature could not be measured accurately due to the large non-uniformities in fluid temperature across the channel cross-section. This would be due to the very large value of C_p near the pseudo-critical point.

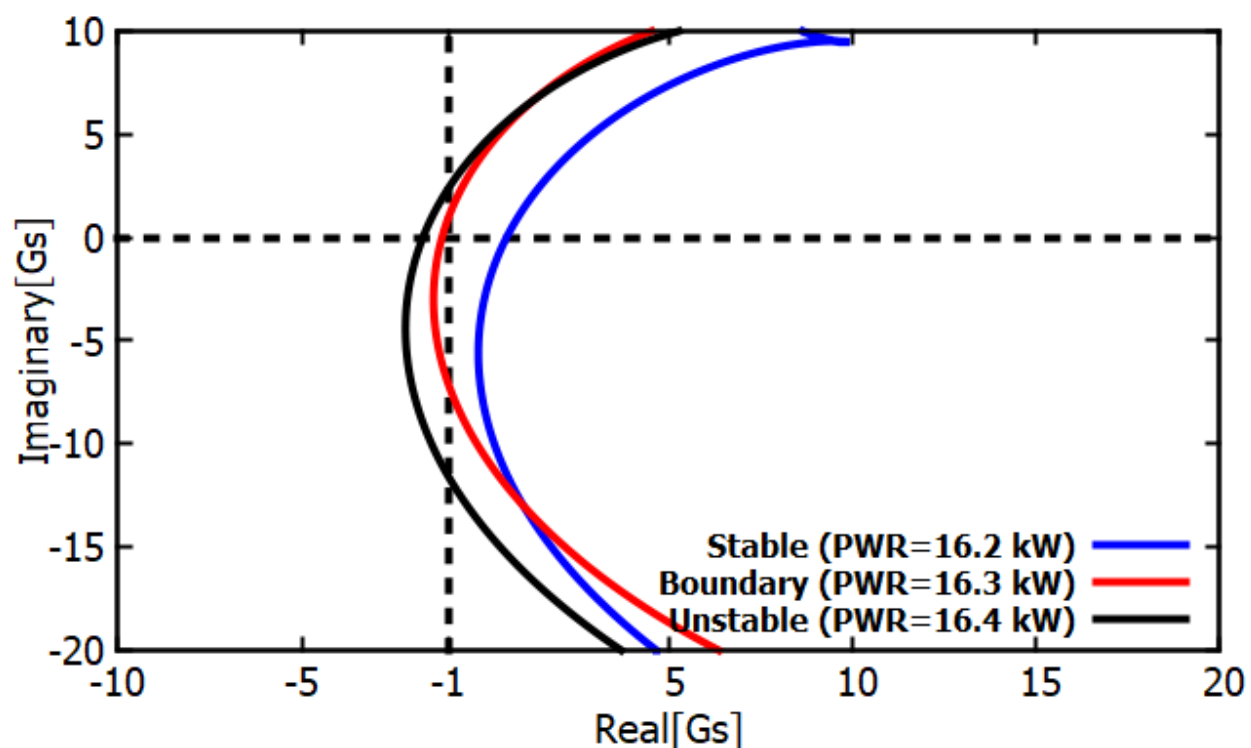


Figure 5.1: Nyquist plot for author's case 1.

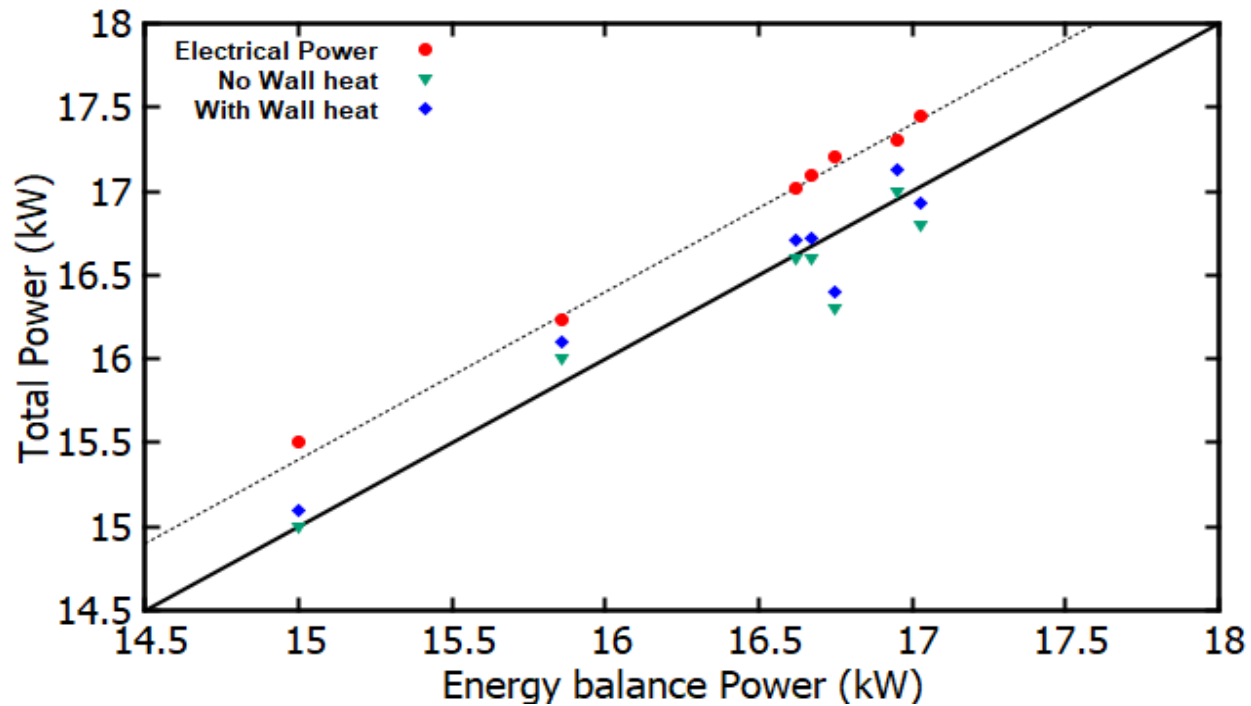


Figure 5.2: Comparison of the threshold powers for the author's cases.

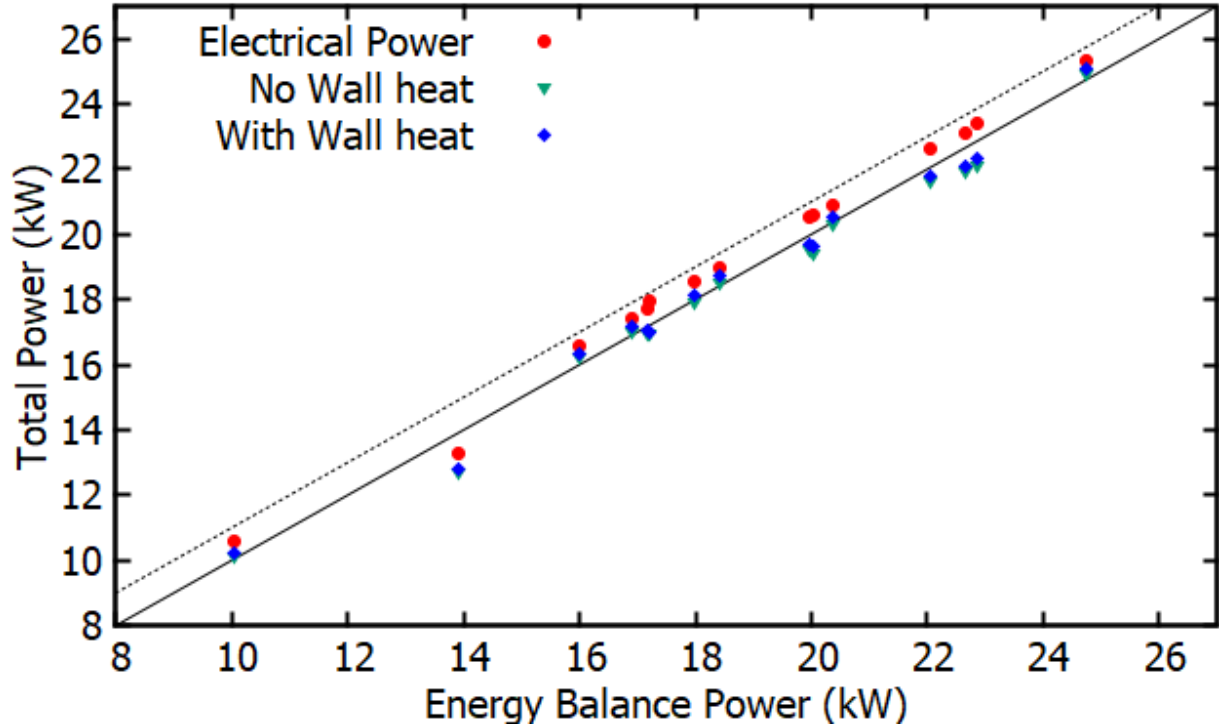


Figure 5.3: Comparison of the threshold powers for Saini's cases.

It is evident from figures 5.2 and 5.3 that the numerical instability boundary powers produced by the 1-D linear program scatter about the energy balance power line but lie below the electrical power line. The numerical results also lie within the experimental uncertainty. The wall-heat storage results show that wall-heat storage slightly increases the stability boundary power, and the agreement with the experiments improved. Tables 5.4 and 5.5 summarize the threshold instability powers predicted by the linear program for the author's and Saini's experimental cases. It is evident that all the numerical results agree well with the experimental data. The negative sign for % difference indicates that the numerical power is below the experimental power, and a positive sign indicates that the numerical power is above the experimental power. The RMS value between experimental and predicted numerical power dropped when considering the wall-heat storage. For the authors' cases, the RMS value between the electrical and numerical

power without and with wall-heat storage are 3.20% and 2.60% respectively. The RMS error between the energy balance and numerical power without and with wall-heat storage are 1.20% and 1.13% respectively. For Saini's cases, the RMS value between electrical and numerical powers without and with wall-heat storage are 4.27% and 3.46% respectively, and the RMS error between the energy balance and numerical power without and with wall-heat storage are 2.90% and 2.55% respectively. This confirms the Linear code's ability to accurately predict the instability boundary in supercritical CO₂ for two parallel channels.

This wall-heat storage finding mimics the previous finding of Ghadge et al. (2020), which was done with water. There they reported that wall-heat storage improved the instability boundary power of two parallel channel water experiments. They stated that the instability boundary power of two slightly dissimilar parallel channels increases slightly when considering wall-heat storage. They also mentioned that the effect of wall-heat storage mostly cancels out between the two channels, and this cancellation effect seems to exist in the present study also.

In Table 5.4 and 5.5 following abbreviations used are as follows:

EL- Electrical

EB- Energy Balance

LP- Linear program

WH- Wall-heat

Table 5.4: Threshold power predictions for author's experimental cases.

Case No.	EL Power	EB Power	LP Power	% Difference	% Difference	LP Power	% Difference	% Difference
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	(kW)	(kW)	(No WH kW)	LP (No WH) vs EL power)	LP (No WH) vs EB power	(WH) (kW)	LP (WH) vs EL power	LP (WH) vs EB power
1.	17.20	16.75	16.3	-5.23	-2.67	16.4	-4.65	-2.09
2.	16.23	15.86	16.0	-1.41	0.88	16.1	-0.80	1.51
3.	17.02	16.62	16.6	-2.46	-0.12	16.7	-1.88	0.48
4.	17.45	17.03	16.8	-3.72	-1.35	16.93	-3.15	-0.76
5.	17.10	16.67	16.6	-2.92	-0.42	16.72	-2.34	0.18
6.	17.30	16.95	17.0	-1.73	0.29	17.15	-1.16	0.88
7.	15.5	15.02	15.0	-3.22	-0.13	15.1	-2.58	0.53
		RMS error =		3.20 %	1.20 %		2.60 %	1.13 %

Table 5.5: Threshold power predictions for Saini's experimental cases.

Case No.	EL Power (kW)	EB Power (kW)	LP Power (No WH kW)	% Difference LP (No WH) vs EL power)	% Difference LP (No WH) vs EB power	LP Power (WH) (kW)	% Difference LP (WH) vs EL power	% Difference LP (WH) vs EB power
1.	13.3	13.9	12.7	-4.51	-8.63	12.8	-3.76	-7.91
2.	20.56	20.05	19.4	-5.64	-3.24	19.6	-4.67	-2.24
3.	25.3	24.76	24.9	-1.58	0.57	25.1	-0.79	1.37
4.	17.97	17.22	16.9	-5.95	-1.86	17	-5.40	-1.28
5.	18.55	17.98	17.9	-3.50	-0.44	18.1	-2.43	0.67
6.	18.97	18.43	18.5	-2.48	0.38	18.7	-1.42	1.47
7.	20.9	20.37	20.3	-2.87	-0.34	20.5	-1.91	0.64
8.	20.5	19.95	19.5	-4.88	-2.25	19.7	-3.90	-1.25

9.	16.57	16.01	16.2	-2.23	1.19	16.3	-1.63	1.81
10.	17.4	16.9	17	-2.30	0.60	17.15	-1.44	1.48
11.	10.6	10.03	10.1	-4.72	0.68	10.2	-3.77	1.70
12.	17.72	17.16	16.9	-4.63	-1.56	17.05	-3.78	-0.64
13.	23.1	22.65	21.9	-5.19	-3.31	22.1	-4.33	-2.43
14.	22.63	22.07	21.6	-4.55	-2.13	21.8	-3.67	-1.22
15.	23.4	22.87	22.1	-5.55	-3.37	22.3	-4.70	-2.49
		RMS Error =		4.27%	2.90%		3.46%	2.55%

5.4.3 Oscillation period

Tables 5.6 and 5.7 gives the oscillation periods produced by the 1-D linear program for author's and Saini's cases. The linear program predicted oscillation periods in good agreement with the experimental oscillation periods especially when the wall-heat storage model was employed. For the author's cases, the RMS error between experimental and numerical prediction reduced from 11.96%, for no wall heat storage, to 7.95% for wall-heat storage. For Saini cases, the RMS error between the experimental and numerical values reduced from 12.13%, for no wall-heat storage, to 8.17% with wall-heat storage. This confirms that the 1-D linear program captures the effect of wall-heat storage on the oscillation period. It predicted reasonably correct oscillation periods in addition to the instability boundary power, making it reliable for engineering use. It also clearly indicates the ability of the 1-D, linear frequency domain solution to predict the oscillation period, and its suitability for flow instability studies.

The oscillation period finding with wall-heat storage also mimics the previous finding of Ghadge et al. (2020) done with water. There they showed that considering wall-heat storage improved the oscillation period predictions when modeling two parallel channels with water. The RMS error between experimental and numerical oscillation period for Xiong et al. (2012) cases without

wall-heat storage was 18%, whereas with wall-heat storage was 11%. For Xi et al. (2014b) cases, the RMS error without-wall heat storage was 12.7% and with wall-heat storage was 7.1%. In addition, Ghadge (2018) using CFD analyses also showed that considering wall-heat storage improved the oscillation period prediction.

Table 5.6: Oscillation period predictions without and with wall-heat storage, author's cases.

Case No.	Experimental Oscillation Period (second)	Oscillation Period (without wall-heat storage) (second)	% Difference	Oscillation Period (with wall-heat storage)	% Difference
1.	7.80	6.92	11.28	7.18	7.95
2.	7.19	6.31	12.24	6.59	8.34
3.	7.20	6.45	10.42	6.69	7.08
4.	6.60	5.69	13.79	5.99	9.24
5.	6.07	5.45	10.21	5.64	7.08
6.	7.19	6.26	12.93	6.62	7.93
7.	6.10	5.34	12.46	5.62	7.87
		RMS error =	11.96 %	RMS error =	7.95 %

Table 5.7: Oscillation period predictions without and with wall-heat storage, Saini's cases.

Case No.	Experimental Oscillation Period (second)	Oscillation Period (without wall heat storage) (second)	% Difference	Oscillation Period (with wall-heat storage)	% Difference
1.	1	0.88	12.00	0.92	8.00
2.	3.2	2.8	12.50	2.93	8.44
3.	3.4	2.94	13.53	3.11	8.53

4.	3.5	3.01	14.00	3.21	8.28
5.	3.2	2.81	12.19	2.93	8.44
6.	2.5	2.21	11.60	2.32	7.20
7.	1.5	1.31	12.66	1.37	8.66
8.	3.4	3.01	11.47	3.15	7.35
9.	5.2	4.62	11.15	4.75	8.65
10.	1.4	1.24	11.43	1.29	7.86
11.	1.9	1.65	13.16	1.72	9.47
12.	2.4	2.14	10.83	2.23	7.08
13.	1.3	1.12	13.85	1.19	8.46
14.	2.8	2.51	10.36	2.58	7.86
15.	3	2.67	11.00	2.78	7.33
		RMS Error =	12.17%	RMS Error =	8.13%

The findings are that, for this present parallel channel system, including the wall-heat storage does not affect much the stability boundary. A similar conclusion was also previously drawn by Ghadge et al. (2020) for H₂O. Thus, it can be concluded that considering wall-heat storage for two parallel channels has only a minor effect on the stability boundary results regardless whether the fluid is CO₂ or H₂O. Therefore, it would be acceptable to ignore the wall-heat storage in determining the stability boundary for two parallel channels, as omitting wall-heat yields conservative results.

5.5 CATHENA results vs. 1-D linear results

Saini (2019) analyzed his experimental work with the commercial CATHENA (v.3.5.4.4) software (Beuthe et al.,2014), a 1-D non-linear program. CATHENA results were already

discussed in the Literature section. Here only, a comparison between the CATHENA and the 1-D linear program results is made. Table 5.8 summarizes the results of Saini's cases obtained from CATHENA code and the 1-D linear program, without the wall-heat storage. Since CATHENA can model water data only, Saini converted back CATHENA results to CO₂ data using same dimensionless parameters, so that comparison between CATHENA and Linear code results can be made. It is evident that the 1-D linear program did a much better job of predicting supercritical flow instability for this present parallel channel system than the non-linear CATHENA (v.3.5.4.4) code. CATHENA results gave an RMS error of 12.12% to the experiment data, whereas the 1-D linear program gave an RMS error of 4.27% to the experiment data. It is also apparent that for 10 cases CATHENA over predicted the instability boundary power compared to the experimental power. This was not expected as experimental power is believed to be greater than the numerical power because of heat losses in the experiment. The wall-heat storage and oscillation period results of CATHENA could not be compared because CATHENA was unable to yield realistic meaningful results. This was already discussed in the Literature section.

Table 5.8: The comparison between the CATHENA and 1-D linear program results, Saini's cases.

Case number	CATHENA results	Linear program without wall results
	% Difference with experimental results	% Difference with experimental results
1.	-12.64	-4.51
2.	6.81	-5.64
3.	-5.67	-1.58

4.	-15.92	-5.95
5.	0.22	-3.50
6.	-9.79	-2.48
7.	-0.57	-2.87
8.	-2.83	-4.88
9.	-22.62	-2.23
10.	-11.78	-2.30
11.	-25.68	-4.72
12.	-12.46	-4.63
13.	9.66	-5.19
14.	4.70	-4.55
15.	5.17	-5.55

Thus, it can be concluded that the 1-D linear program did a much better job of predicting supercritical flow instability in parallel channels than the non-linear CATHENA (v.3.5.4.4) code for both CO₂ and H₂O.

5.6 Effect of wall-heat storage thickness on stability boundary power

A parametric study of the effect of wall-heat storage thickness on the stability boundary power of the system was done for author's case 2. The stability boundary power was analyzed using different wall-heat storage thickness and results are presented in Table 5.9. It is apparent from the results that with increase in wall-heat storage thickness, the stability boundary power increases up to certain limit. Thereafter, it remains constant with further wall-heat storage thickness increase. This finding mimics with the previous finding of Ghadge et al. (2020) done with water.

Table 5.9: Effect of wall-heat storage thickness on the system stability boundary power, author's Case 2.

Wall-heat storage thickness	Stability boundary power
0 mm (No wall-heat storage)	16.00 kW
1.245 mm (Actual wall thickness)	16.10 kW
2.0 mm	16.34 kW
2.5 mm	16.42 kW
3.0 mm	16.55 kW
3.5 mm	16.55 kW
4.0 mm	16.55 kW

5.7 Search of Static Instability through numerical analyses

Since for all experimental cases, the oscillatory flow instability was observed, and no static flow instability was found. More experiments at low temperatures (which is favorable condition for static instability) were not performed because of financial constraints. Therefore, it was decided to perform numerical analyses in search of temperature favorable for static flow instability.

From numerical analyses, it was found that for this two vertical up-flow parallel channel CO₂ loop, the static flow instability is not possible. Numerical analyses were done using linear program up to minimum of temperature -54.0 °C. Table 5.10 gives the details of case conditions that were analyzed in search of static flow instability. For all cases, the channel inlet K-factors were 1.2 and 1.3, and mass flow rate was 0.6 kg/sec. For all cases, oscillatory instability was observed. No static instability was found.

Table 5.10: Different case conditions in search of static flow instability.

Case No.	Channel Inlet Temperature [°C]	Channel outlet K-factor
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		Ch 1	Ch 2
1.	-20	20	30
2.	-30	30	40
3.	-43	20	30
5.	-43	30	40
4.	-54	20	30
5.	-54	30	40
6.	-54	40	50
7.	-54	50	60
8.	-54	60	70
9.	-54	70	80

Previous numerical findings done in search of static instability for a single channel flow revealed that static instability is possible at low temperatures. Yeylaghi et al. (2011) and Chatoorgoon (2013) reported existence of static flow instability with H₂O and CO₂ for vertical down-flow orientation. For vertical up-flow and horizontal flow orientation, they reported static instability with H₂O. They also revealed that the vertical up-flow was the orientation least likely to exhibit static flow instability compared to vertical down-flow and horizontal flow. Ambrosini (2011) reported static flow instability using R23 in a single horizontal channel. Ebrahimnia et al. (2016) reported static flow instability with water in single vertical up-flow channel. From above findings, it is apparent that numerical analyses were performed only for a single channel (Present system is two vertical up-flow channels) and none of them reported static flow instability with CO₂ in vertical up-flow channel.

Based upon present numerical analyses done in search of static flow instability, it is concluded that for this two vertical up-flow parallel channel CO₂ loop, static instability is not possible.

However, previous numerical findings shows static flow instability is possible for single up-flow channel system when using fluid other than CO₂; therefore, there might be chances of getting static flow instability for this two parallel channel system if fluid other than CO₂ is used. Future students will investigate that part.

5.8 Assessment of the Dimensionless parameters

As already discussed in the experimental section, water data is the most relevant because of the use of supercritical water as the working fluid in nuclear reactors. But H₂O experiments were not performed because the University personnel became fearful of the high temperatures and pressures involved, leaving us no option but to use CO₂ instead. However, experimental CO₂ instability data was converted to equivalent H₂O data using Ambrosini and Sharabi dimensionless parameters.

Since it is important to know how accurate the converted equivalent H₂O data is. Therefore, in this section, the feasibility of using the dimensionless parameters of Ambrosini and Sharabi (2008) to accurately convert experimental CO₂ instability data to H₂O is examined. Earlier, Ambrosini (2011) using different numerical analyses tools proved that these parameters perform very well for scaling supercritical flow instability data between different fluids (Water, CO₂, R23 and Ammonia). Herein these parameters are again assessed but in different way, using CO₂ instability experimental data in combination with the numerical results. This assessment will also verify the predictions made by Ambrosini (2011). The procedure for it is discussed below.

Ambrosini and Sharabi's dimensionless parameters, for a given geometry and given set of K factors, for supercritical flow are:

$$N_{spc} = \frac{\beta_{pc}}{C_{p,pc}} (h_{pc} - h_{in}) \quad (5.2)$$

$$N_{tpc} = \frac{P}{m} \frac{\beta_{pc}}{C_{p,pc}} \quad (5.3)$$

The limitation imposed on these parameters by Ambrosini (2011) is that it can only convert CO₂ data to H₂O data or vice-versa only when the N_{spc} is in range of 0.5-2.0. For present experimental cases, the N_{spc} value lie between that range, 0.9-1.13. The N_{spc} and N_{tpc} data of the seven experiments are again presented in Table 5.11. This data was used to model water in the same loop with the same K -factors. The equivalent inlet temperature for water was obtained by using the N_{spc} value and assuming a system pressure for water. The procedure for calculating inlet temperature is explained below.

$$(N_{spc})_{CO_2} = (N_{spc})_{water} \quad (5.4)$$

$$(N_{spc})_{CO_2} = \left(\frac{\beta_{pc}}{C_{p,pc}} (h_{pc} - h_{in}) \right)_{water} \quad (5.5)$$

Once a system pressure for water was assumed, 23 MPa say, the values of β_{pc} , $C_{p,pc}$, and h_{pc} were calculated using the NIST property package. The h_{in} value was determined by inserting the values of $N_{spc, co2}$ and β_{pc} , $C_{p,pc}$, and h_{pc} for water in equation 5.5. The equivalent inlet temperature for water was calculated from NIST with the h_{in} obtained at 23 MPa pressure. For determining the equivalent instability boundary power for water, the N_{tpc} value was used. The procedure to calculate the equivalent instability boundary power for water is explained below:

$$(N_{tpc})_{CO_2} = (N_{tpc})_{water} \quad (5.6)$$

$$(N_{tpc})_{CO_2} = \left(\left(\frac{P}{m} \right)_{exp} \frac{\beta_{pc}}{C_{p,pc}} \right)_{water} \quad (5.7)$$

$$\text{Where} \quad (m_{exp})_{water} = (\rho_{in})_{water} * \left(\frac{m_{exp}}{\rho_{in}} \right)_{CO_2} \quad (5.8)$$

As the dimensionless parameters were derived for a constant Froude number at the channel inlet, the equivalent mass flow rate for water was determined by using the same inlet velocity for both CO₂ and water. By inserting the values of $N_{tpc, co2}$ and β_{pc} , $C_{p, pc}$, and m_{exp} for water in equation 5.7, the equivalent value of the experimental instability boundary power for water was determined. Table 5.11 summarizes the dimensionless parameters and the derived equivalent experimental instability data for water.

Table 5.11: Dimensionless parameters and dimensionless analysis instability data for water.

Case No.	N_{spc}	N_{tpc}	Equivalent inlet temperature (Water), [° C]	Equivalent experimental instability boundary power (Water), [kW]	Pressure (Water) [MPa]	Mass flow rate (Water) [kg s ⁻¹]
1.	1.023	1.680	337.43	51.26	23	0.055150
2.	1.125	1.686	328.28	50.70	23	0.054040
3.	1.084	1.706	332.02	51.41	23	0.054532
4.	1.085	1.790	331.90	55.17	23	0.055874
5.	1.082	1.780	332.20	55.54	23	0.056136
6.	1.130	1.735	327.78	51.88	23	0.054019
7.	0.993	1.646	339.99	49.77	23	0.054341

The next step was to use the 1-D linear program to determine the instability boundary for water and compare these values with those obtained through the dimensionless parameters. Because of the previous instability work of Ghadge et al. (2020) with water, we know that the linear code predicts the water experiments with at least 95% accuracy. Therefore, it would be fruitful to

compare the stability boundaries from the dimensionless analysis and the linear code analysis.

Table 5.12 summarizes these results.

Table 5.12: Comparison of the dimensionless analysis results with the linear analysis results.

Case No.	Dimensionless Analysis Boundary power (kW)	Linear Analysis Boundary power (kW)	% Difference
1.	51.26	49.40	3.64
2.	50.70	48.60	4.15
3.	51.41	50.20	2.36
4.	55.17	53.20	3.58
5.	55.54	53.50	3.68
6.	51.88	50.70	2.27
7.	49.77	48.10	3.36

The RMS error between the dimensionless analysis boundary power and the linear code analysis boundary power for water is 3.35 %. This agreement is very good. Therefore, it is confirmed that the dimensionless parameters proposed by Ambrosini and Sharabi (2008) are accurate enough to scale the CO₂ data to water within proposed range of N_{spc} (0.5-2.0, described by Ambrosini and Sharabi), with the same geometry and K -factors. This also shows that presented equivalent water data is accurate.

Chapter 6 Summary, Conclusions, and Recommendations

6.1 Summary

In the present research work, both theoretical and experimental studies were conducted to get an insight into supercritical flow instability occurring in two vertical parallel channels. Seven experiments using CO₂ flowing upwards were performed at low inlet temperatures to enrich the limited experimental database and search for the occurrence of static instability. A 1-D linear in-house program developed by previous researchers was used for the first time for flow instability studies with supercritical CO₂. The effect of the wall-heat storage model on the flow instability was also investigated. In addition, the accuracy of Ambrosini and Sharabi's (2008) dimensionless parameters proposed, to convert CO₂ supercritical flow instability data to water, was examined. Following are the conclusions that were drawn from the present research work along with key findings:

6.2 Experimental & Numerical Conclusions

6.2.1 Experimental Conclusions

- a) Oscillatory flow instability was observed for all experimental cases. No static instability was found experimentally. Further experiments at low inlet temperatures in search of static instability were not performed because of financial reasons. The static instability was not found for this CO₂ two parallel channel system with numerical analyses (1-D Linear program). Future students will investigate static instability of this two parallel channels system.

Key findings

- a) At a low input power, the flow rate between the channels was symmetric. With an increase in input power, it redistributed between the channels and became asymmetric. With further input power increase, the flow rate oscillated 180° out-of-phase as expected.
- b) The oscillation period was between 1-2 times the fluid transit time through the channel. This agrees with the previous finding for two-phase flow.
- c) The difference between experimental electrical and energy balance power was between 2-3% for all experimental cases. This difference was attributed to heat loss to the surroundings.

6.2.2 Numerical Conclusions

- a) The 1-D linear program accurately predicted the flow instability boundary in two heated vertical parallel channels with supercritical CO_2 flowing upward. Previously, Ghadge et al. 2020 showed it was 95% accurate for water experiments. Overall, this validates the numerical methodology used in 1-D linear frequency domain program for flow stability studies. Now, the program can help further for supercritical flow instability studies in various geometries and configurations like three channels, down and horizontal flow without necessarily performing expensive experiments, thus, saving overall cost. The information about the numerical methodology used in the 1-D linear program is also very useful to other researchers who wish to develop programs for flow stability studies.
- b) The wall-heat storage results show that including wall-heat storage slightly increases the stability boundary power in a two parallel-channel system, and the agreement with the experiments improves. Most of the wall-heat storage effect between the two channels

cancels out, as previously reported by Ghadge et al. 2020. Because wall-heat storage showed a very small effect on the instability boundaries; therefore, the wall-heat storage effect could be ignored in determining the stability boundary for a two parallel channel system.

- c) The 1-D linear program was able to capture the accurate oscillation period and oscillation period prediction improved when considering the wall-heat storage effect. This makes the program more reliable to flow stability studies. This has shown the suitability of 1-D linear frequency domain solution for oscillation period prediction along with flow instability boundary.
- d) Assessment of Ambrosini and Sharabi (2008) dimensionless parameters showed good agreement within 95% of accuracy. Therefore, the dimensionless parameters of Ambrosini and Sharabi (2008) are very useful for converting the CO₂ data to water within the same geometry, for the same *K*-factors.

Key findings

- a) The change in convective heat-transfer coefficient value has a small effect on flow instability boundary for two parallel channel system when using the wall-heat storage model.
- b) With an increase in wall-thickness, the flow instability boundary for two parallel channel system increases only up to a certain thickness, and thereafter, it remains constant with further wall-thickness increase.

Previous researchers reported bad numerical results using the wall-heat storage effect (Debrah et al. 2013; Sharma et al. 2015; Liu et al. 2018, Saini 2019) and chose not to further report

modeling with the wall-heat storage. This study is the second to report good results and good agreement with the experiment using the wall-heat storage effect. Ghadge (Ghadge 2018; Ghadge et al. 2020) was the first to report good agreement; however, that study was performed with supercritical water. It shows that including the wall-heat storage effect in a 1-D linear code gives closer predictions to the experimental data for two parallel channel system irrespective of fluid used either CO₂ or water.

6.3 Recommendations

- a) A supercritical flow pump can be installed to study vertical down-flow.
- b) Fluid can be replaced with R23 to study static flow instability.
- c) A larger size accumulator can be installed to regulate the loop pressure instead of manually controlling it with needle valves.

List of Publications

Journal

1. Experiments and Analyses of supercritical CO₂ flow instability with study of wall heat storage and dimensionless parameters. Applied Thermal Engineering. (Conditionally accepted, Under-process)

Conference

1. Experiments on supercritical flow instability in two vertical parallel channels. DOI: 10.11159/icffts20.125, Proceeding of the International Conference on Fluid Flow and Thermal Science (ICFFTS'20), Virtual Conference- September 9-10, 2020.

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