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Development and analysis of a novel scaling methodology for stability appraisal of supercritical flow channels

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ABSTRACT

The prospect of achieving higher thermal efficiency with simpler plant design, projects Supercritical water reactor as a better futuristic option compared to its boiling water counterpart. However, performing lab-scale experiment with supercritical water, particularly for appraisal of stability performance, is an arduous task, considering the level of pressure and temperature involved. That necessitates scaling analysis for the development of reduced-scale models to simulate true-scale prototype under lab-level constraints. Present study, therefore, attempts to develop a scaling methodology focused on stability analysis and to identify a less-restrictive model fluid, while proposing generalized scaling rules preserving the phenomenological physics. US reference design of SCWR is selected as the prototype. Four characterizing dimensionless groups are recognized from the non-dimensional conservation equations under imposed pressure boundary condition, while the system pressure for the model fluid is identified noting the region of similarity on the plane of non-dimensional density and non-dimensional pressure. Two-zone lumped parameter model is developed encompassing the thermalhydraulic, fuel dynamics and power dynamics equations, which are subsequently employed for linear stability analysis and also for transient simulations. Both approach produced identical stability maps, leading to a generalized representation. R134a is concluded to be the most suitable model fluid from both power and pressure point of view.

1. Introduction

Supercritical fluids have several scientific and industrial applications as coolant, solvent, carrier or reagent. Chemical industries employ supercritical water (SCW) as substitute of the organic solvents, while it is also used for producing decaffeinated coffee powder and for creating nanomaterials through supercritical fluid decomposition process (https://en.wikipedia.org/wiki/Supercritical_water_reactor). One of the most significant applications of SCW is in the nuclear power industry. Its large heat capacity around the pseudocritical point allows substantial energy transfer through a small mass of coolant, whereas the high operating temperature promises enhanced cycle efficiency. Accordingly the concept of supercritical water reactor (SCWR) has emerged as one of the most powerful ideas under the generation-IV reactor technology and is expected to be operational in the near future (~2025). As on date, at least four different designs are under scrutiny, with each one in different stages of commercialization. While the Korean design is exploring the concept of a 1400 MWe core with a cruciform-type U/ZrH_2 solid moderator to counter the requirement of additional neutron moderation, the Canadian version developed and optimized a 64-element fuel assembly (Dominguez et al., 2016). Gen-IV International Forum (GIF) aims to test a small-scale fuel assembly in a reactor and finalize the prototype dimensions within the ongoing ten-year-plan (https://www.gen-4.org/gif/jcms/c_9352/technology-roadmap).

Considering the extreme operating conditions associated with the SCWR and possible consequences of any unforeseen event, it is essential to investigate all possible aspects of such a system at the laboratory scale, prior to its commercialization. Accordingly researchers have shown general interest towards both the heat transfer and stability behavior of supercritical flow systems since the inception of the present millennium. While the current trend of research is inclined towards numerical and computational analyses, the role of experiments can never be undermined, particularly in the context of understanding unfamiliar phenomenon and exploring newer physics. Unfortunately the associated volume of experimental literature is rather limited. The review work of Cheng and Schulenberg (2001) emphasizes on the scarcity of reliable experimental data in the typical parameter ranges for SCWR, which consequently presents a huge hurdle in accurate description and prediction of SCWR thermalhydraulics. That highlights

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Nomenclature

A	area (m^2)
C	precursor density (cm^{-3})
C_f	heat capacity of fuel rod ($kJ\,K^{-1}$)
C_p	isobaric specific heat ($kJ\,kg^{-1}\,K^{-1}$)
D_h	hydraulic diameter (m)
f	friction factor (–)
g	gravitational acceleration ($m\,s^{-2}$)
G	mass flux ($kg\,m^{-2}\,s^{-1}$)
h	enthalpy ($kJ\,kg^{-1}$)
k	feedback reactivity (–)
K	restriction coefficient (m^{-1})
L_c	core/channel length (m)
n_f	number of fuel rods (–)
N_{Eu}	Euler number (–)
N_{Fr}	Froude number (–)
N_{SPC}	Sub-pseudocritical number (–)
N_{TPC}	Trans-pseudocritical number (–)
p	pressure ($N\,m^{-2}$)
P	power (kW)
q''_o	heat flux ($kW\,m^{-2}$)
t	time (s)
T	absolute temperature (K)
z	space coordinate (m)

Greek Symbols

α	heat transfer coefficient ($kW\,m^{-2}\,K^{-1}$)
β	volumetric expansion coefficient (K^{-1})
Δp	pressure drop ($N\,m^{-2}$)
ρ	density ($kg\,m^{-3}$)
π_h	heated perimeter (m)

Subscripts and superscripts

a	accelerational
c	core/channel
f	fuel rod/Friction
g	gravitational
i	inlet
L	loss
m	model
o	outlet
p	prototype
pc	pseudocritical
r	reference
ss	steady-state
$*$	dimensionless quantities

the need of developing experimental facilities and subsequently necessitates phenomenological scaling, as it is impracticable to replicate the SCWR condition at the lab-scale. Therefore several attempts towards the scaling of supercritical flow systems are available in the open literature. Jackson and Hall (1979) identified several important requirements for scaling of heat transfer in supercritical fluids. Starting from the dimensionless versions of the conservation equations, three dimensionless groups were proposed for the scaling of pressure, bulk temperature and mass flux. Heat flux and heat transfer coefficient were defined accordingly. Number of recent CFD-based efforts can be found, focussing on the associated mechanism of heat transfer. Pioro and Duffey (2007) reviewed the fluid-to-fluid modeling of heat transfer at supercritical conditions. Based on the phenomenological analysis and distortion approach of Ahmad (1973), a fluid-to-fluid scaling law was proposed, which was subsequently validated using existing test data from various fluids, combined with existing heat transfer correlations.

Another important perspective of SCWR operation is the system stability, which is comparable with the well-explored boiling water reactor (BWR). A two-phase flow system can experience several types of instabilities (Bouré et al., 1973; Kakac and Bon, 2008), which are commonly classified as either static or dynamic. Density-wave oscillations (DWO) is a pure dynamic instability, originated because of the continuing interactions between flow variables and corresponding feedback effect to modify the nature of the cause of its initiation itself. It can mathematically resemble a set of governing equations with multiple competing solutions, which do not allow the system to settle into any one of them. Khabensky and Gerliga (2013) presented an excellent discussion on the generalization of the experimentally observed and theoretically predicted thermalhydraulic instabilities in the thermal and nuclear installations. They identified the vertical channels with specified pressure-drop boundary condition to be more prone to DWO, owing to the pronounced role of the gravitational pressure drop. In a typical BWR core, fluid density can change from 740 kg/m^3 to 180 kg/m^3, thereby leading to instability. Across several proposed designs of SCWR (US, European and Japanese versions), the density change can be even more drastic, i.e., from about 777 kg/m^3 to 90 kg/m^3 (Ruspini et al., 2014). Therefore it is logical to expect both static and dynamic instabilities inside the SCWR core, and the same has been reported by several researchers through both experiments (Xiong et al., 2012; Zhang et al., 2013) and computations (Ortega Gómez et al., 2008; Su et al., 2013; Yi et al., 2005). Majority of the researches are, however, numerical in nature. Volume of relevant experimental data is rather limited, making the validation of the corresponding code difficult (T'Joen and Rohde, 2012).

While the threshold of the static instability can be predicted from the steady-state versions of the conservation laws, the dynamic version must take into account different dynamic factors like the propagation time, inertia and compressibility. Therefore the methodologies followed during heat transfer scaling are inadequate to lead to identical stability behavior and a separate treatment is essential. Considering the similarities between the boiling channels of BWR and heated supercritical channels, scaling principles are developed following similar approaches. Marcel et al. (2009) developed scaling procedure to use a mixture of R-125 and R-32. With a system pressure of 6.2 MPa, it showed excellent similarities with SCW at 25 MPa. This mixture, however, has severe restrictions in terms of flammability limit and chemical stability, and requires accurate monitoring of the mixture composition. Furthermore, they applied the same scaling rule to both the radial and axial directions, leading to rather small radial dimension of the experimental facility, and hence resulting in undesirably large frictional pressure drop. Rohde et al. (2011) proposed an improved scaling procedure mainly for natural circulation systems based on R-23 as the model fluid. System pressure, power and temperature levels were significantly reduced, while preserving the dynamics of the system. Practical issues, such as the onset of heat transfer deterioration, was also touched upon in their work. They, however, introduced two multiplication factors for scaling for the flow rate and friction factor respectively, which require experiment-based empirical relations, and hence are not universal. The formulation proposed by Ambrosini and Sharabi (2008), following a homogenous approach similar to the boiling channels, also suffer from similar dependence on experiments for incorporating the constitutive laws across the pseudocritical point.

Therefore the primary objectives of the present study is to identify a less restrictive model fluid, which can properly mimic the SCW under the relevant scaled condition of an SCWR, and to define the scaling rules in a generalized way, so as to preserve the phenomenological