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Flow analysis of an innovative compact heat exchanger channel geometry

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ABSTRACT

In the framework of CEA R&D program to develop an industrial prototype of sodium-cooled fast reactor named ASTRID, the present work aims to propose an innovative compact heat exchanger technology to provide solid technological basis for the utilization of a Brayton gas-power conversion system, in order to avoid the energetic sodium–water interaction if a traditional Rankine cycle was used. The aim of the present work is to propose an innovative compact heat exchanger channel geometry to potentially enhance heat transfer in such components. Hence, before studying the innovative channel performance, a solid experimental and numerical database is necessary to perform a preliminary thermal–hydraulic analysis. To do that, two experimental test sections are used: a Laser Doppler Velocimetry (LDV) test section and a Particle Image Velocimetry (PIV) test section. The acquired experimental database is used to validate the Anisotropic Shear Stress Transport (ASST) turbulence model. Results show a good agreement between LDV, PIV and ASST data for the pure aerodynamic flow. Once validated the numerical model, the innovative channel flow analysis is performed. Principal and secondary flow has been analyzed, showing a high swirling flow in the bend region and demonstrating that mixing actually occurs in the mixing zone. This work has to be considered as a step forward the preposition of a reliable high-performance component for application to ASTRID reactor as well as to any other industrial power plant dealing needing compact heat exchangers.

1. Introduction

Compact heat exchangers deserve an increasing attention for 4th generation nuclear reactors due to their potential application in several components of a nuclear power plant. Such components are of particular interest when dealing with fluids with low thermal capacity, i.e. gases. Therefore, potential applications to GFRs using S-CO_2 as thermal fluid for the power conversion cycle (Dostal et al., 2004; Nikitin et al., 2006; Tsuzukiet al., 2007; D.E Kim et al., 2008) or to GFRs using traditional gas Brayton power conversion cycle have been investigated (Pope et al., 2009; Gezelius, 2004). In this sense, applications to VHTRs have also been foreseen (Kim et al., 2009; McCormack, 2001; Aquaro and Pieve, 2007; E.S. Kim et al., 2008; Pra et al., 2008; Mylavarapu et al., 2009; Kim and No, 2011; Figley et al., 2013). Applications to SFRs are more recent and still limited to S-CO_2 Brayton cycle cases (Lee and Lee, 2014) or to the design of auxiliary components such as the intermediate heat exchanger (Mochizuki and Takano, 2009) or the DHRS heat exchanger (Vinod et al., 2013), where their compactness could help the feasibility of the proposed design. While studies are still ongoing on possible SFR power conversion systems (Zhao and Peterson, 2008; Perez-Pichel et al., 2011; Ahn and Lee, 2014), the CEA is currently evaluating the technical feasibility of using a Brayton gas-power conversion system to prevent sodium–water interaction hazard in the framework of the ASTRID project (Abonneau et al., 2014). The CEA proposed a first-of-a-kind sodium-gas heat exchanger based on PCHE technology (Cachon et al., 2014), where the sodium-gas heat exchanger would couple the secondary sodium loop with the tertiary nitrogen loop (Cachon et al., 2015).

The basic design of the sodium-gas heat exchanger is that of traditional plate heat exchangers and consists of a number of steel plates accommodating either sodium or gas channels. These plates are superposed to obtain the basic configuration shown in Fig. 1.

Since the design of the gas-side of the sodium-gas heat exchanger is fundamental (because it essentially determines the heat transfer resistance of the heat exchanger), it is worth studying innovative geometries enhancing the heat transfer performance of the gas side and therefore the compactness of the component. The present paper aims to propose a new heat transfer pattern for the gas side of the ASTRID sodium gas heat exchanger and to study its thermal–hydraulic behavior. This is a necessary starting point to eventually demonstrate the

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List of acronyms

ASTRID	advanced sodium technological reactor for industrial demonstration
CEA	French Atomic and Alternative Energy Commission
GFR	Gas-cooled fast reactor
S-CO_2	Supercritical-carbon dioxide
VHTR	Very High Temperature Reactor
SFR	Sodium-cooled Fast Reactor
DHRS	Decay Heat Removal System
PCHE	Printed Circuit Heat Exchanger
3D	3 dimensional
ASST	Anisotropic Shear Stress Transport model
ρ	Fluid density
U_i	i-component of the velocity field
u'_i	i-component velocity fluctuation
k	Turbulence kinetic energy
ω	Turbulence specific dissipation rate
μ_t	Eddy viscosity
LDV	Laser Doppler Velocimetry
2-C LDV	2-component LDV
PIV	Particle Image Velocimetry

heat transfer enhancement provided to the component. Note that, if the proposed heat transfer geometry has been developed for the gas side of the ASTRID sodium-gas heat exchanger, it is potentially applicable to any industrial situation where compact heat exchangers play a key role.

2. Innovative channel geometry description

The innovative channel geometry is shown in Fig. 2. It is supposed to be one of the gas channels shown in Fig. 1. In particular the channel can be thought as the result of the superposition of two single PCHE wavy channels in phase opposition (white and yellow in Fig. 2).

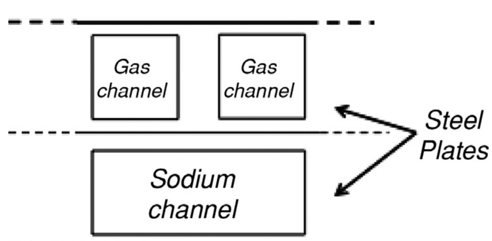

Fig. 1. Basic configuration of ASTRID sodium-gas heat exchanger.

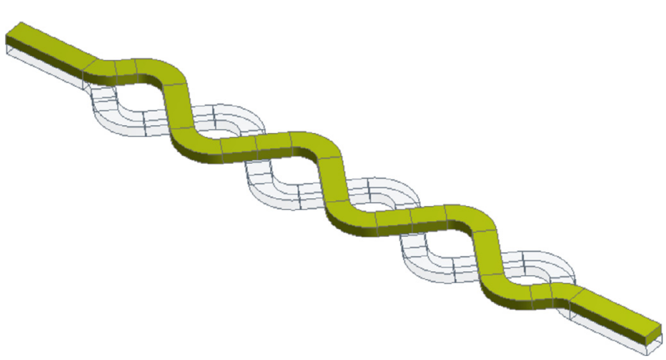

Fig. 2. Superposed channels identification. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

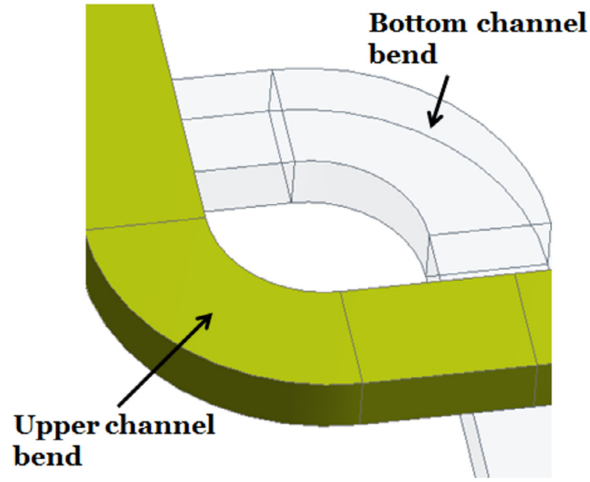

Fig. 3. Bend definition for each pair of channel.

Considering the PCHE plate (consisting of several parallel wavy channels), the actual fluid stream is composed by several wavy channels intersecting each other in several points, creating a fully 3D flow.

The innovative channel is composed by elementary geometrical elements, specifically bends, straight channels and mixing zones. The bends are present in each of the two superposed wavy channels composing the innovative channels: Fig. 3 identifies the upper channel and bottom channel bend.

The mixing zone can be thought as the region corresponding to the intersection of the two superposed channels: they can communicate each other through an “open window” called mixing plane. Here mass, momentum and heat transfer are supposed to be strongly enhanced. See Fig. 4 for visual explanation. The straight duct links the bends with the mixing zones.

It is worth noting that the innovative channel allows a large number of design options in terms of geometrical parameters: for example the designer has to set the half channel cross-section geometry, the proper angle with regard to the fluid principal direction, the straight duct length between two bends, the bend curvature radius.

While the choice of the latter three geometrical parameters can be done arbitrarily (and therefore they will be specified whenever necessary in the present paper), the half channel cross-section geometry could potentially be of any shape. A hypothesis is made at this concept stage with regard to the total innovative channel cross-section. In particular the reference half channel cross-section for the innovative channel is rectangular, with the shorter side equals to half the longer side.

See that bends and mixing zones are supposed to create a strong fluid deformation, resulting in an important secondary motion (i.e. not only led by pressure gradient) in the bend flow. Moreover, since the bend flow itself creates secondary motion (typically Dean vortices), the actual flow is supposed to be very three-dimensional with a continuous detachment and reattachment of the boundary layer.

The complexity of the flow is thought to be responsible for the mass, momentum and heat transfer enhancement. This phenomenological description is the objective of the numerical study and validation. The following sections describe the adopted approaches for the numerical and experimental validation.

3. Numerical model formulation

Aiming to build a solid numerical model to study the innovative channel flow, a realizable Anisotropic Shear Stress Transport (ASST) model has been proposed (Vitillo et al., 2015). The ASST model is supposed to improve SST model results especially for secondary