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Preliminary verification of a transient analysis code TSACO for helium cooled system

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ABSTRACT

This work mainly focuses on the verification process of the thermal-hydraulic and safety analysis code (TSACO) applied to the Chinese helium-cooled ceramic breeder test blanket module cooling system. The HE-FUS3 facility, which is an integral test facility for helium cooling systems, has been chosen to assess the capability of the TSACO code. The steady state and transient behavior of two loss-of-flow accidents (LOFAs) were simulated by TSACO. The steady state temperature distributions of the two LOFA tests were well reproduced by TSACO. The transient results of mass flowrates and outlet temperatures predicted by TSACO at the compressor and test section compared well with the experimental data. The good agreement between the calculated results and experimental data verifies the capability of the TSACO code to simulate helium cooling systems. In addition, an uncertainty analysis was conducted for the test section outlet temperatures of LOFA30 and LOFA50. The power, inlet temperature, mass flowrate, physical material properties, and heat transfer models were chosen as the input uncertainty parameters. The results show that the experimental data are easily covered by the uncertainty bands calculated by TSACO during transient analysis. This demonstrates the accuracy and fidelity of the TSACO code.

1. Introduction

Helium is widely used as a coolant in the cooling systems of various nuclear reactors, such as high-temperature gas-cooled reactors and the Chinese helium-cooled ceramic breeder test blanket module (CH HCCB TBM) (Zheng et al., 2009; Xiang et al., 2010). A thermal-hydraulic and safety analysis code (TSACO) for helium cooling systems has been developed (Jie et al., 2013) using a semi-implicit, finite-difference method. The heat transfer and friction factor correlations for helium are incorporated in TSACO. The Chinese HCCB TBM cooling system has been chosen to verify TSACO through a comparison of RELAP5/MOD3. A steady state investigation of these two codes has been conducted with the same initial and boundary conditions. The results are in good agreement with those obtained by RELAP5 (Jie et al., 2013). The critical flow model in TSACO also exhibits good agreement. The analysis of in-vessel LOCA has been carried out by TSACO. The first wall (FW) temperature, system pressure, vacuum vessel (VV) pressure, and mass of helium released into the VV have been calculated. Verification of the hydrodynamic model, heat structure model, auxiliary models, and numerical methods of TSACO should be further investigated.

This paper focuses on verifying TSACO based on the HE-FUS3 facility, which is a continuation of previous investigations. TSACO is mainly verified by assessing simulation results against experimental data from two Loss of Flow Accident (LOFA) transient scenarios in the HE-FUS3 facility. To evaluate the capability of the system code to predict a given scenario accurately, an uncertainty analysis should be conducted alongside the reference case (Freixa et al., 2013). Thus, an uncertainty analysis based on the HE-FUS3 facility was also carried out to further verify TSACO.

2. Description of TSACO

For single-phase flow, the mass, momentum, and energy conservation equations are as follows:

$$\frac{\partial \rho}{\partial t} + \frac{1}{A}\frac{\partial W}{\partial z} = 0 \tag{1}$$

$$\frac{\partial W}{\partial t} + \frac{\partial}{\partial z}\left(\frac{W^2}{\rho A}\right) = -A\frac{\partial p}{\partial z} - \rho g A - \frac{f}{D_e}\frac{\rho A u^2}{2} \tag{2}$$

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$$\frac{\partial(\rho h)}{\partial t}+\frac{\partial(\rho uh)}{\partial z}=\frac{q''_W P_h}{A}+\frac{\partial p}{\partial t} \tag{3}$$

and the coolant state equation is:

$$\rho=\rho(p,h) \tag{4}$$

where ρ, t, A, W, z, p, f, D_e, u, and h denote the fluid density, time, flow channel area, mass flow rate, axial distance, pressure, friction factor, equivalent hydraulic diameter of flow channel, velocity, and specific enthalpy, respectively; q''_W is the heat flux and P_h is the heated perimeter.

2.1. The integral form of the heat conduction equation is

$$\iiint_V (\rho C_p)\frac{\partial T}{\partial t}dV=\iiint_V q_V dV+\iint_S k\frac{\partial T}{\partial x}dS \tag{5}$$

where (ρC_p) is the volumetric heat capacity, V is the volume, q_V is the internal heat source, S is the surface, k is the thermal conductivity, and x is the spatial coordinate.

The mathematical and physical models are based on the cooling system design and characteristics. These include the hydrodynamic model, heat structure model, and other auxiliary models such as the circulator model, friction factor model, wall heat-transfer model, abrupt area change model, critical flow model, and radiant heat transfer model. A semi-implicit finite-difference method and staggered-grid mesh scheme are adopted to find numerical solutions. This method has been applied by many researchers for the solution of both single- and multi-phase problems (Jeong et al., 1999; Harlow and Amsden, 1971; Liles and Reed, 1978).

The TSACO thermal-hydraulic analysis code was developed in Fortran 90. Detailed model descriptions and numerical solutions have been introduced in previous reports (Jie et al., 2013).

3. HE-FUS3 facility description

Within the framework of the European Fusion Technology Program, ENEA obtained financial support from the EU in 1993 for a helium facility construction, named HE-FUS3 (Meloni, 2008a; Meloni and Polidori, 2009). This facility was designed for the thermal mechanical testing of prototypical module assemblies for the DEMO reactor, and is being used in the European Helium Cooled Pebble Bed (HCPB) Blanket design, which is to be tested in the International Thermonuclear Experimental Reactor. The facility is located at the ENEA Brasimone Laboratories in Italy. Within the framework of the RAPHAEL Integrated Project (Hittner et al., 2006), the experimental data have been offered by ENEA for a benchmark exercise aimed at validating the Very High Temperature Reactor (VHTR) transient analysis code.

The eight loop configuration (Meloni, 2008a; Geffraye et al., 2012) shown in Fig. 1 supplies the helium flowrate to an experimental Test Section (TS), where the mock-up of the HCPB Blanket can be tested (Dell'Orco et al., 2000). The test section consists of a 7-pin bundle of height 3 m and 50 kW of single electrical power for a total power of 350 kW. The loop is separated into two zones, as shown in Fig. 1. These two figure-of-eight closed loops work at different temperatures. The cold zone includes a compressor and the other parts of the TS. An economizer, placed at the crossover point, recovers the gas enthalpy before recirculating the helium through the compressor. Thereby, it is possible to reduce both the external power needed to obtain the required temperature at the TS inlet and the cooler size required to reduce the compressor inlet temperature to the maximum continuative operating temperature. The main design parameters for the HE-FUS3 facility are listed in Table 1 (Dubey et al., 2011).

4. Uncertainty analysis methodology

Best-estimate codes are used to perform more realistic calculations, and uncertainty analysis is a necessary complement. The goal of uncertainty analysis is to provide best-estimate simulations with uncertainty bands, taking into account uncertainties in the code modeling capabilities as well as uncertainties in the initial and boundary conditions of a given transient scenario (Dubey et al., 2011). The analysis of the HE-FUS3 facility for LOFA30 and LOFA50 has been carried out by Geffraye and Meloni using RELAP5 and CATHARE2 (Meloni and Polidori, 2009; Geffraye et al., 2012). Most of the results showed a good agreement with the experimental data, especially the mass flowrates and pressure drop. However, the test section outlet temperatures for LOFA30 and

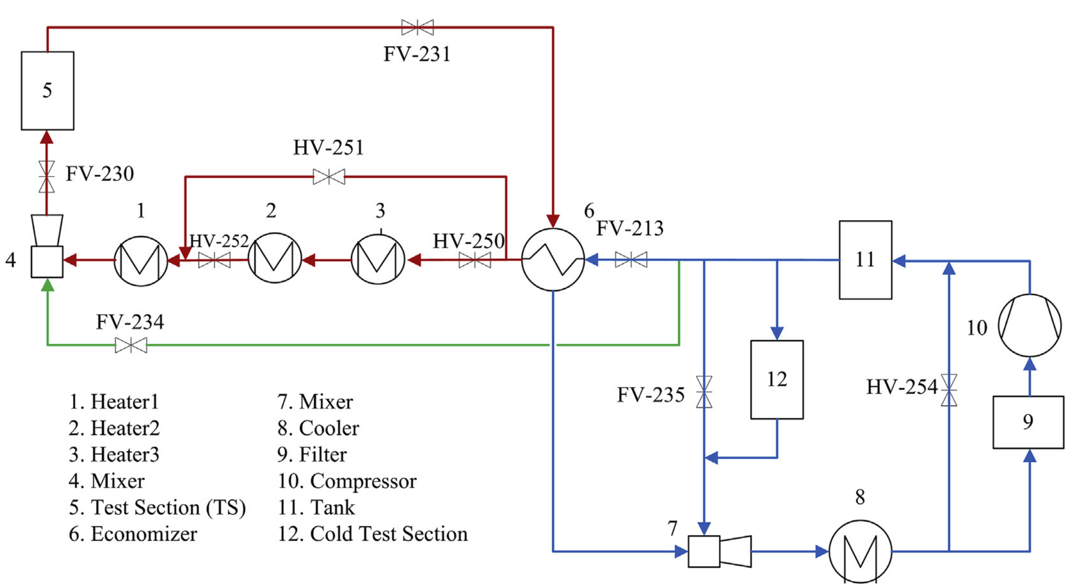

Fig. 1. HE-FUS3 loop layout.

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