Annals of Nuclear Energy 73 (2014) 96–107

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Preliminary study of coupling CFD code FLUENT and system code RELAP5

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ARTICLE INFO

Article history:
Received 13 February 2014
Received in revised form 20 June 2014
Accepted 22 June 2014
Available online 10 July 2014

Keywords:
Explicit coupling method
DLL
FLUENT
RELAP5

ABSTRACT

The present paper discusses a coupling strategy of the 3D (three-dimensional) computational fluid dynamics (CFD) code ANSYS-FLUENT with the best estimate 1D (one-dimensional) thermal–hydraulic system code RELAP5/MOD3.1. Preliminarily, by using DLL (Dynamic Link Library) technology and FLUENT UDF (User Defined Functions), an explicit coupling method expected to be able to support the analysis of multi-purpose thermal–hydraulic phenomena in nuclear reactor systems has been developed. Calculations for two test cases using the coupled FLUENT/RELAP5 code have been carried out to test and demonstrate the coupling capability: (i) the first one consisting of single-phase water transient flow in a square straight tube with well controlled mass flow rates; (ii) the second one illustrating the process of single-phase water flow in a system including two closed loops and one vessel, on which loss of loop water flow due to pump trip and increase of loop water temperature are studied. Both reasonable 1D systematic behaviors and 3D distribution information are naturally obtained for the test cases. Besides, a study of a highly transient experiment problem, i.e. Edwards–O'Brien pipe blowdown problem, has been performed by using the coupled FLUENT/RELAP5 code. The results are compared with standalone RELAP5 calculation and available experimental data, which shows the coupled FLUENT/RELAP5 code's acceptable potential for the capability of analyzing either simple single-phase or complex two-phase flow problem.

1. Introduction

Best-estimate nuclear system codes such as RELAP5 (Reactor Excursion and Leak Analysis Program), TRAC (Transient Reactor Analysis Code), RETRAN (RElap4 TRANsient), ATHLET (Analysis of THermal–hydraulics of LEaks and Transients), CATHARE (Code for Analysis of THermalhydraulics during an Accident of Reactor and safety Evaluation), are widely used to investigate the thermal–hydraulic characteristics of the nuclear power plants (NPPs) either under normal steady-state or during various accident scenarios. These computer codes are mainly one-dimensionally programmed with many well-considered constitutive models, to account for sophisticated phenomena in multi-phase flow and heat transfer in large-scale plant facilities without unreasonably time-consuming computations. On the other hand, the application of CFD codes like CFX and FLUENT (ANSYS, 2011) to analyze important and noticeable 3D effects in nuclear industry, are also under development for use especially in nuclear reactor safety (NRS) (Bestion, 2010; Mahaffy et al., 2007; Smith, 2007). Therefore, combining the advantages of widely used system codes and 3D CFD codes is a hopeful endeavor to include important 3D thermal–hydraulic effects in nuclear reactor design beyond accident scenarios. Potential use of coupled 3D/1D codes in nuclear primary system lies in boron dilution scenarios, main steam line break scenarios, pressurized thermal shock, and thermal mixing in the downcomer and lower plenum of RPV etc. The couplings between CFX and RELAP5-3D (Aumiller et al., 2001, 2002), CFX and ATHLET (Papukchiev et al., 2009), FLUENT and RELAP5-3D (Anderson, 2006; Yan, 2011), CFX and TRACE (Bertolotto et al., 2009) have been investigated mainly using the technology of parallel virtual machine (PVM) (Geist et al., 1994) or DLL (Hart, 2005).

Explicit or semi-implicit coupling methodology could be taken into consideration according to how the involved codes cooperate with each other to advance to the calculation for the next new time-step for a transient problem. Explicit methodology requires that the data are exchanged between the codes only once for each time-step. However, for the semi-implicit methodology, the data are exchanged several times for each time-step until convergences of the coupled parameters are reached. A method to explicitly couple FLUENT and RELAP5/MOD3.1 addressing time-dependent problems is discussed in this paper. In this method, RELAP5 in the form of a Windows DLL file is called by FLUENT at the end of every time-step through FLUENT User Defined Functions (UDFs). With this method,

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http://dx.doi.org/10.1016/j.anucene.2014.06.042
0306-4549/

FLUENT and RELAP5 could run simultaneously on their respective domains to complete the simulation on the entire domain. Selected physical variables can be exchanged during the coupling to deal with different cases such as single- or multiple-phase, closed or open loop coupling. To test and demonstrate the coupling method, analyses of one single-phase test case, one water-steam two-phase experiment problem and one more comprehensive test case including loops and vessel are performed using coupled FLUENT/RELAP5 and standalone RELAP5 or FLUENT and compared with each other. The results show that the coupling method is feasible and credible and could have a wide variety of practical applications in nuclear thermal–hydraulic technologies.

2. Coupling method

Information exchange between FLUENT and RELAP5 is realized with the help of DLL technology and FLUENT UDF feature. DLL is a shared library concept implemented by Microsoft in Windows operating systems. As with Windows executable file (EXE), a DLL can contain code, data and resources shared with external "master" programs loading and executing the DLL. RELAP5 DLL can be treated as a single function that is dynamically accessible for other codes, e.g., FLUENT (through UDFs). To successfully call the functions in RELAP5, essential entry points have been properly placed in the subroutines such as those responsible for code initialization and transient advancement. As a "slave" processor, RELAP5 should be able to be executed at least once for every iteration or time-step by FLUENT, which can be naturally implemented by directly using UDFs. UDFs allow one to customize FLUENT and enhance its capabilities. UDFs can be used to customize boundary conditions and material property definitions, initialize a solution, perform on demand execution of a UDF, execute at the end of an iteration step for steady case or at the end of a time-step during transient advancement and so on. While FLUENT UDFs are collections of functions belonging to C language, using UDFs to call RELAP5 DLL just involves mixing language programming between C and FORTRAN both of which are extensively popular programming languages. The previous works of coupling FLUENT and RELAP5 were mainly done with the help of PVM. For the explicit coupling methodology, using PVM may require more complex coding in RELAP5. The DLL method in this work is relatively simple to implement in RELAP5 and FLUENT UDF. However, PVM seems to be more suitable for realizing semi-implicit coupling. This is because semi-implicit coupling splits a time-step into several iterations between FLUENT and RELAP5 to complete the calculation for this time-step. While the DLL file is executed as a whole, it is hard to exchange intermediate variables between FLUENT and RELAP5 during execution of the coupled code for each time-step.

The simplified explicit coupling scheme is shown in Fig. 1. FLUENT and RELAP5 read their respective input files formally. Besides that, some necessary information about the RELAP5 volumes and junctions containing the physical variables are to be exchanged with FLUENT is specified in the UDFs. Then the information is passed to RELAP5 for use of exporting data. After a successful initialization, RELAP5 advances for the first time-step and exposes acceptable time-step size to FLUENT. The reason why RELAP5 is preferred to run first is that RELAP5 has a well-designed scheme of time-step size control based on the check on some criterions such as the material Courant limit, mass errors, material properties out of defined ranges, water property errors (Shieh et al., 2001). In this way adaptive time-step size synchronous with that in RELAP5 could be achieved in FLUENT, which is essential to perform a complete calculation before advancing to the calculation for the next time-step. According to different coupling situations different sets of physical parameters are needed to be exchanged on the coupling boundaries between the two codes. After the boundary conditions for FLUENT have been updated, the FLUENT solver starts inner iterations until converged solution has been obtained at the end of a successful time-step for transient run.

For the RELAP5 volume *Ri* connected to FLUENT boundary cells, the energy and continuity conservation equations are collected to produce the pressure equation:

$$\delta P_{Ri}^{n+1} = a_{R,i}^{n} + \sum_{k=NC+1}^{NJ} b_k^n v_{fk}^{n+1} + \sum_{k=NC+1}^{NJ} c_k^n v_{gk}^{n+1} + \sum_{j=1}^{NC} d_j^n W_{fj}^{n+1} + \sum_{j=1}^{NC} e_j^n W_{gj}^{n+1} \tag{1}$$

where the pressure difference δP^{n+1} is $P^{n+1} - P^n$; the superscript n represents the n-th time-step; V_{fk}^n and V_{gk}^n are the liquid and gas phase velocities at the interior junction k respectively; W_{fj}^n and W_{gj}^n are the liquid and gas phase mass flow rates at the coupling junction J respectively; NC is the number of the coupling junctions; NJ is the total number of junctions that are attached to the volume *Ri*. The coefficients $(b_k^n, c_k^n, d_k^n, e_k^n)$ contain donored quantities for gas and liquid phase internal energies, void fraction, densities of gas and liquid phases, and non-condensable gas quality if present.

Momentum conservation equation for the junction connecting RELAP5 volume and FLUENT cells can be written using the pressure difference between the RELAP5 volume and the averaged pressure in the FLUENT boundary cells as follows:

$$v_{fj}^{n+1} = \beta_{fj}^n + \epsilon_{fj}^n (\delta P_{Ri}^{n+1} - \delta P_F^{n+1}) \tag{2}$$

$$v_{gj}^{n+1} = \beta_{gj}^n + \epsilon_{gj}^n (\delta P_{Ri}^{n+1} - \delta P_F^{n+1}) \tag{3}$$

where δP_F^{n+1} is the pressure difference averaged over the FLUENT boundary cells that interface with the RELAP5 volume *Ri*.

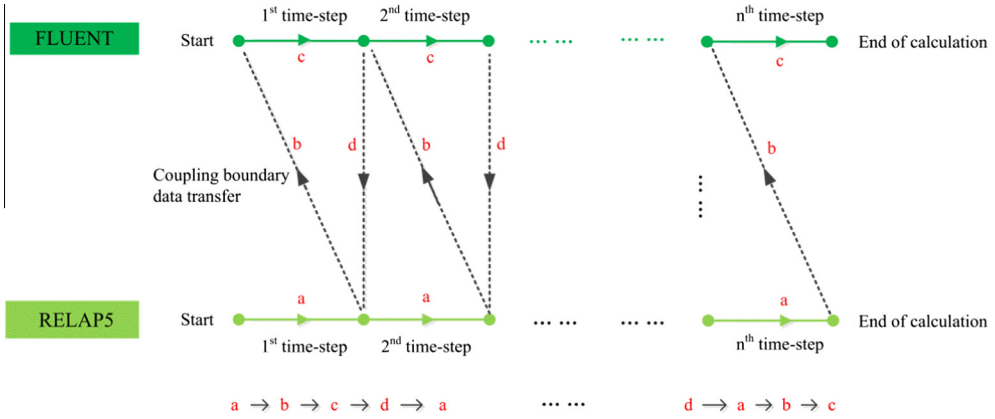

Fig. 1. Simplified explicit coupling scheme.