Progress in Nuclear Energy 76 (2014) 160–182

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Theory and implementation of nuclear safety system codes – Part I: Conservation equations, flow regimes, numerics and significant assumptions

Glenn A. Roth*, Fatih Aydogan

University of Idaho, Center for Advanced Energy Studies, 995 University Blvd., Idaho Falls, ID 83401, United States

ARTICLE INFO

Article history:
Received 3 February 2014
Received in revised form
23 April 2014
Accepted 13 May 2014
Available online 14 June 2014

Keywords:
System code comparison
Nuclear plant analysis
RELAP
TRACE
CATHARE
ATHLET

ABSTRACT

The design and analysis of the thermal/hydraulic systems of nuclear power plants necessitates system codes that can be used in the analysis of steady-state and transient conditions. Due to the dispersed development of system codes over many laboratories and universities, there are several system codes available for use. Many of the available codes have multiple similar versions developed for specific user needs.

The code comparisons provided in the two parts of this article series allow users to select the appropriate system code for their specific problems. In this comparison, the governing equations for mass, momentum and energy conservation are evaluated. It will be shown that the governing equations do not vary substantially between the codes considered. Most of them utilize a lumped approach with only two fields to represent two phase flow.

Two-phase flows are divided into flow regimes based on their appearance and the flow structure. The regimes are used to select appropriate closure relationships to model heat transfer, interfacial drag, and other flow conditions.

In addition, major assumptions about the governing and closure equations in these codes are compared and discussed. The most significant of the assumptions is that the governing equations can be discretized in time.

The numerical approach of the codes is compared to one another since the numerical approach not only affects the speed of the system codes but also the accuracy of the results.

In the second part of this article, the closure relations, their major assumptions, experimental verification and validation are discussed.

The results of these articles also guide the development of these system codes, the underlying thermal/hydraulic models, and indicate areas where models must be improved to adequately address issues with new reactor design and development activities.

1. Introduction

Nuclear reactor systems are complex, and require detailed analysis to evaluate reactor performance during normal operations as well as accident or transient conditions. Computer codes that are used to analyze these complex reactor systems are called "system codes". System codes are used in the design and analysis of nuclear reactors. They can be used to evaluate steady-state performance of reactor systems, and are also used for transient analyses. The system codes can aid reactor system engineers in refueling evolutions, relicensing efforts with regulatory agencies, and applications for reactor plant power uprating.

System codes include detailed models of reactor components, such as pipes, pressurizers, valves, and pumps. These hydrodynamic models have frequently been extended to include a code capability to model multiple phase flows. The interaction between coolant phases is modeled in order to capture heat transfer properties and mass exchange between the phases. Components that model heat transfer through materials, as well as nuclear heat generation are also part of system code analyses. System codes also include basic control elements that can be used to implement reactor control systems such as pump trips, reactor scrams, and other automated system responses.

* Corresponding author.
E-mail addresses: roth1581@vandals.uidaho.edu (G.A. Roth), fatih@uidaho.edu (F. Aydogan).

http://dx.doi.org/10.1016/j.pnucene.2014.05.011
0149-1970/

This work compares and contrasts the capabilities, performance, and validation of many of the modern system codes, such as RELAP, TRAC, TRACE, COBRA/TRAC, CATHARE, and ATHLET. These codes are compared by providing detailed information about the conservation equations implemented in each code, along with the flow regimes considered, numerical solution methods, and the significant simplifying assumptions. Because code performance is characterized by many additional factors, a second part of this article compares further code characteristics of closure relations, code validation, and significant code limitations.

2. Conservation models

Conservation equations vary between the system codes, but the basic equations for conservation of mass, momentum and energy are consistent. The mass, momentum, and energy conservation equations can be written for each phase in the system. Doing this for the vapor and liquid phases results in the what is referred to as the six-equation model. Fig. 1 shows a simplified characteristic hydraulic system and illustrates the challenges in modeling two-phase hydrodynamic systems. The complexity can be demonstrated by considering the exchange of mass, momentum, and energy between the phases shown in Fig. 1. Although the system depicted in Fig. 1 is fairly simplified, more complex flow regimes are often modeled by system codes, and will be addressed later.

The interactions between the liquid phase and the vapor phase take several forms. Droplet entrainment is one method for mass transfer between the liquid and vapor phase. Liquid droplet entrainment is due to:

- Interactions with hydraulic structures (such as rector fuel bundle spacer grids)
- Viscous effects (droplets "breaking off" into the vapor flow).

Droplets are re-entrained when they impact the liquid/vapor interface or coalesce into larger droplets that form a large enough volume to no longer be considered droplets. The vapor phase may also be entrained in the liquid phase in the form of bubbles by similar mechanisms. Different shapes and sizes of bubbles must be represented by different governing equations in reality, but modeling simplifications use just a few equations to represent them. Mass exchange between the phases is also accomplished by converting one phase to the other. This exchange of mass is accompanied by energy transfer, which is added to or removed from the liquid or vapor phase by:

- Direct contact with the container walls
- Radiation heat transfer from the liquid or wall surface to the entrained droplets
- Convection to/from the vapor phase at the phase interface or at the bubble or droplet interfaces.

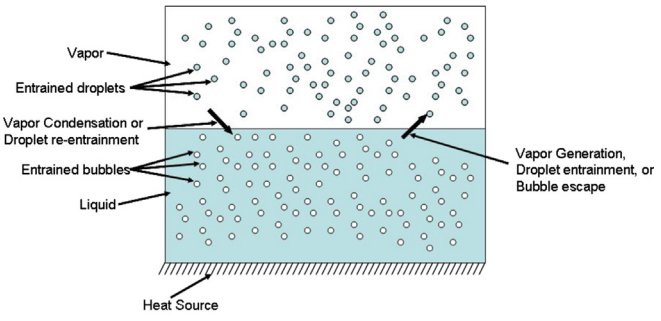

Fig. 1. Generic two-phase system.

These heat transfer mechanisms can increase the temperature in the liquid phase until it reaches the saturation temperature, and the liquid begins to transition to the vapor phase. The same is true in reverse, where the vapor phase can condense into liquid. This can occur at the liquid/vapor interface, as well as at droplet or bubble interfaces. The droplets and bubbles will grow or shrink, depending on the direction of heat flow. The conservation equations used by the system codes attempt to model the exchange of mass and energy in the two-phase system. The RELAP5 codes (MOD3, MOD3.3, 3D, SCDAP) model two phases (liquid and vapor) for each of the three conservation equations. The resulting six equations give this model its name; the "six-equation model". The conservation equations for one-dimensional components are shown in the following sections.

2.1. RELAP5 governing equations

2.1.1. 1D component mass conservation

$$\frac{\partial}{\partial t}(\alpha_k\rho_k)+\frac{1}{A}\frac{\partial}{\partial x}(\alpha_k\rho_k v_k A)=\Gamma_k \tag{2.1.1}$$

where the subscript k indicates the phase, either vapor (g) or liquid (f). The first term on the left hand side of Eq. (2.1.1) is the time rate of change of the mass of phase k. The second term is the change in mass of phase k due to the mass entering or leaving the control volume. The Γ_k is the volumetric mass exchange rate of phase k. The mass conservation equation formulation does not consider mass sources or sinks. This results in a requirement that the mass lost from one phase must be acquired by the other. Thus, $\Gamma_f = -\Gamma_g$. The momentum equation has been written in "area-average" notation. RELAP assumes that the total mass transfer can be partitioned into contributions from mass transfer at the vapor/liquid interface near the wall (Γ_w) and interfacial mass transfer in the bulk fluid (Γ_{ig})

2.1.2. 1D component momentum conservation

$$\begin{aligned}\alpha_k\rho_k A\frac{\partial v_k}{\partial t}+\frac{1}{2}\alpha_k\rho_k A\frac{\partial v_k^2}{\partial x}=&-\alpha_k A\frac{\partial P}{\partial x}+\alpha_k\rho_k B_x A-(\alpha_k\rho_k A)FW_k\cdot v_k\\&+\Gamma_k A(v_{kI}-v_k)-(\alpha_k\rho_k A)FI_k\cdot(v_k-v_r)\\&-C\alpha_k\alpha_r\rho_m A\left[\frac{\partial(v_k-v_r)}{\partial t}+v_r\frac{\partial v_k}{\partial x}-v_k\frac{\partial v_r}{\partial x}\right]\end{aligned} \tag{2.1.2}$$

Note that the momentum conservation equation is written in terms of momentum per unit volume using the velocity variables v_g and v_f. The spatial variation of the momentum terms is expressed in terms of $v_g^2$and v_f^2. The momentum conservation written this way can be reduced to the Bernoulli equation for steady, incompressible, and frictionless flow.

The momentum equation has a reduced effect on the solution when compared to the mass and energy equations. This is due to the fact that reactor flows are dominated by large sources and sinks of momentum (pumps and abrupt area changes).

This formulation of momentum conservation assumes that the phasic pressures are equal, and that the interfacial pressure is the same as the phasic pressures (except for stratified flows). Phasic viscous stresses are neglected, but are considered at the interface. Interface force terms include both the viscous and pressure stresses. Wall forces are assumed to be modeled by the variable area momentum flux formulation.