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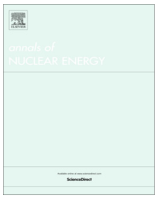

Solving the six-field governing equations for a system code

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ABSTRACT

The coolant systems of nuclear power plants are modeled with system codes. The results of the system code calculations are necessary not only to develop new power plants, but also in the licensing and analysis of existing power plants. Therefore, it is essential that system codes produce realistic results.

Simple models using a single fluid field have been used in initial versions of many system codes. In recent years, more fluid fields have been used for best-estimate code results to improve two-phase flow predictions of the system codes. This paper introduces the numerical equations and solution methods for a next-generation system code that uses 6 fluid fields. It demonstrates the discretization of the mass, momentum, and energy governing equations and the application of matrix solutions that are necessary to implement the 6-field model in a software code.

1. Introduction

The first nuclear system codes for reactor analysis were limited to very basic models that were able to model only a single fluid field (Mesina, 2016). A single fluid field does not allow for very detailed modeling of reactor transients. Developments in the RELAP code in the late 1960's and early 1970's included the addition of a second field to allow for calculation of 2-phase transients, along with the accompanying boiling heat transfer models (Mesina, 2016). The two-field model has been used by many system codes since that time (Spore et al., 2001; U.S. Nuclear Regulatory Commission, 2008).

More recent developments in nuclear system codes have included updates to the number of fields modeled by the governing equations. The addition of a droplet field helps to model the transition to superheat conditions, as well as the complex heat transfer of a reflood condition. The W-COBRA/TRAC-TF2 code now includes a droplet field that is available in the 3D vessel component (Frepoli et al., 2010), though there is a single energy equation for the liquid film and the droplet field, which implies that both fields share the same temperature. The TRACE code will soon include a droplet field to improve reflood modeling (U.S. Nuclear Regulatory Commission, 2008).

The addition of a droplet field improves the results for reflood conditions. The NRC is also considering development of a bubble field for the TRACE code for further transient model improvements (Bajorek, 2008; Shack, 2008). Specialized TRACE versions have been developed that include bubble fields (Talley et al., 2013).

Another thermal–hydraulic analysis code called Safety and Performance Analysis Code for Nuclear Power Plant (SPACE) is being developed by Korean nuclear industry (Ha et al., 2009; Kwak et al., 2014). The SPACE code has governing equations for two-fluid, three-field flows in 1D or 3D geometries. Models that calculate the rate of entrainment and de-entrainment of droplets were developed and included in the SPACE code as described in Schimpf et al. (2018).

Additional fields have been included in the RELAP code by merging the COBRA-TF code with RELAP5 (Lee et al., 2017). The MARS code is based on RELAP5 and COBRA-TF (Jeong et al., 2016). The COBRA-TF code includes the capability of calculating two fluids and three fields, as well as subchannel calculations. A variant of COBRA-TF (COBRA-IE) has also been developed that is a general purpose system analysis code. The COBRA-IE code includes models for three-field counter-current flow (Aumiller et al., 2015).

Increasing the number of fields improves the results for transient reactor analysis. Kunz et al. (1998) developed a multi-field two-phase model and showed that increasing the number of fields improves the results for transient two-phase analysis. Roth and Aydogan showed (Roth and Aydogan, 2015) a set of governing equations for a six-field model. The equations balance mass, momentum, and energy for a continuous liquid and continuous vapor field, as well as large and small fields of bubbles and droplets. Increasing the fidelity of the fluid model by increasing the

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Nomenclature

Greek

α	Volume fraction
α_e	Volume fraction of entrained droplets
χ	Turbulent kinetic energy dissipation rate per unit mixture mass
ϵ	Wall vapor generation/condensation flag. $\epsilon = 1$ for boiling in the boundary layer, $\epsilon = -1$ for condensation.
η_e	Grid efficiency factor
Γ	Volumetric mass exchange rate $\left(\frac{kg}{m^3 \cdot s}\right)$
λ	Wavelength
μ	Dynamic viscosity
ρ	Density
σ	Surface Tension
ς	Pipe diameter-dependent coefficient
ζ	Droplet turbulent diffusivity

English

Δt	Change in time from one timestep to the next (timestep size)
ΔX	Cell height
$\overline{u}_t$	average turbulent eddy velocity
A	Flow area
A	Interfacial area
A_c	Area of the channel
A_f	Flow area of pipe
A_g	Area of the grid
$A_{i,6}$	Interfacial area concentration for small bubbles
$A_{i,d}$	Droplet interfacial area concentration
B_x	Body forces (gravity)
C	Coefficient of virutal mass (from momentum equations)
$C_{D,k}$	Drag coefficient of leading group k bubble in wake entrainment
C_d	Empirical constant – 4.8
$C_{RC,k}$	Proportionality constant
C_{RC2}	Proportionality constant
$C_{RC}^{(2)}$	Empirical coefficient for large bubble coalescence
$C_{RC}^{(k)}$	Empirical coefficient for bubble coalescence
C_{SO}	Shear off coefficient – 3.8×10^{-5}
$C_{TI}^{(k)}$	Adjustable coefficient – 0.03
$C_{WE}^{(k)}$	Experimental determined coefficient for wake entrainment between two large bubbles
$C_{WE}^{(k)}$	Wake entrainment coefficient for bubble coalescence
D	Diameter
D_{hy}	Hydraulic Diameter
D_I	Diameter of droplet impacting spacer grid
D_o	Initial droplet diameter
$DISS$	Energy dissipation term
FW	Wall drag coefficient in energy dissipation and momentum equations $\left(\frac{1}{sec}\right)$
G	Gap of the flow channel
g	Gravity
h'	Phasic specific enthalpy for wall (thermal boundary layer) interface mass transfer
h^*	Phasic specific enthalpy (for bulk interface mass transfer)
$H_{k,m}$	Heat transfer coefficient from field k to field m per unit volume
$H_{m,k}$	Heat transfer coefficient from field m to field k per unit volume
$HLOSS$	Dynamic flow loss in liquid phase resulting from abrupt area changes. Code-computed or user-input values.
k'_A	Empirical Constant
k_D	Local droplet deposition velocity
L_{cell}	Length of computational cell
m_E	Mass of droplets entering the grid
P	System pressure
P_H	Heated Perimeter
P_p	Perimeter of pipe
P_w	Wetted Perimeter
Q	Volumetric heat addition rate $\left(\frac{W}{m^3}\right)$
Q_G	Gas volumetric flow
r	Radius
R_c^*	Dimensionless radius of curvature for cap bubble
$R_{SO,c}$	Critical radius of curvature for bubble shear off
Rc	Radius of curvature
S	Ratio of drop velocity to gas velocity
S	Source term
s_k	Liquid or vapor multiplier. Set to 1 for vapor phases and -1 for liquid phases
T	Temperature
t	Time
T^s	Saturation temperature
U	Internal energy
V	Volume of the hydro cell
v	Velocity
$v_{4,crit}$	Critical vapor velocity
V_{cell}	Volume of computational cell
V_c	Critical volume
V_{dI}	Velocity of drop impacting spacer grid
VIS_k	Artificial viscosity term for field k, where k is 1 or 4.
W	Longer width of flow duct
W_{LE}	Mass flow of entrained drops
W_{LFC}	Critical mass flow liquid film
W_{LF}	Mass flow liquid film
$We_{c,TI,k}$	Critical Weber number for turburlent breakup of small bubbles – 6.5
x	Direction of flow

Subscripts

1	Continuous liquid field
2	Large Droplet
3	Small Droplet
4	Continuous vapor field
5	Large Bubble
6	Small Bubble
b	Bubble value (field numbers 5 or 6)
d	Droplet value (field numbers 2 or 3)
i	Field interface
K	Center of volume upstream of calculation volume
k	Field subscript – any of the 6 fields
L	Center of current calculational volume
l	Leading (bubble field)
max	Maximum value
rel	Relative value
T	Trailing (bubble field)
t	Total value
w	Value at the wall, wall

Superscripts

$'$	Indication of phasic specific enthalpy for heat transfer in the thermal boundary layer near the wall
$*$	Indication of phasic specific enthalpy for bulk heat transfer
$\dot{X}$	“Donored” value – volume weighted avereage at a junction from adjacent volumes
$\sim$	Provisional value
n	“Old” time value
$n+1$	“New” time value