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ABSTRACT

The scaling of thermal hydraulic systems is of great importance in the development of experiments in laboratory-scale test facilities that are used to replicate the response of full-size prototypical designs. One particular phenomenon that is of interest in experimental modeling is the quench front that develops during the reflood phase in a PWR (Pressurized Water Reactor) following a large-break LOCA (Loss of Coolant Accident). The purpose of this study is to develop a scaling methodology such that the prototypical quench front related phenomena can be preserved in a laboratory-scale test facility which may have material, geometrical, fluid, and flow differences as compared to the prototypical case. A mass and energy balance on a Lagrangian quench front control volume along with temporal scaling methods are utilized in developing the quench front scaling groups for a phenomena-specific second-tier scaling analysis. A sample calculation is presented comparing the quench front scaling groups calculated for a prototypical Westinghouse 17 x 17 PWR fuel design and that of the geometry and material configuration used in the FLECHT SEASET series of experiments.

INTRODUCTION

In order to simulate actual systems (prototypes), laboratory-scale experiments are usually performed at a reduced size, with the option of using different materials, different working fluids, and different fluid conditions. The objective of the laboratory experiment is to capture the phenomena that have been determined to be important for the understanding of the full size system. Scaling analyses are normally performed to verify that smaller sized laboratory experiments will represent the full size system.

Scaled experiments have been used for years in the areas of fluid mechanics for airfoil design, hydraulics for ship design, as well as water tables for harbor designs and heated effluent discharges. Scaling fluids have been used in heat transfer studies to simulate high pressure fluids and other dangerous working fluids to examine critical heat flux behavior and core melt conditions. More recently, scaling has been used to simulate

the thermal-hydraulic conditions expected in a nuclear reactor for postulated accident conditions. There has been a scaling methodology proposed by Zuber, et al. [1] that is focused on the scaling of such phenomena that exist in a nuclear power plant under accident conditions. Wulff [2] and Ishii [3] present similar scaling methods for single- and two-phase systems.

The generalized scaling approach that has been developed by Zuber for thermal-hydraulic systems [1] employs a two-tier scaling approach. An important aspect of Zuber's approach is that the scaling process can be used to help identify the most important phenomena as well as the less important phenomena such that when compromises are made, the important phenomena are correctly simulated and preserved.

In the two tier scaling approach developed by Zuber, the first tier is a "top-down" scaling (first tier) that gives a scaling group for each transfer process as derived from the dimensionless control volume equations for the conservation of mass, momentum, and energy as written for the thermal-hydraulic system. The scaling groups that result from the normalization of the control volume equations are time ratios for the different processes that occur in the system. These groups are called "Pi" parameters. Top-down scaling provides a method to identify the important phenomena, derive similarity groups, provide weighting of the different groups to establish priorities, and to develop a basis for decoupling fast and slow transients which have different time scales. The top-down scaling approach, which is applied to both the experiment and the prototype, or full-scale system, can identify the lack of similarity between the test and the prototype thereby identifying scaling distortions.

The "bottom-up scaling" approach (second tier) addresses only those thermal-hydraulic processes that are identified as being important or can have distortions that could impact the experiment. Bottom-up scaling focuses on the particular phenomena to develop a specific Pi term in the system, and the equations that govern the particular phenomena of interest. The bottom-up scaling can be used to characterize the transport terms in the control volume equations (transport of mass, momentum or energy), establish the relationships for calculating these terms and compare the scaled experiment to the full size prototype.

Since the primary focus of many reflood heat transfer tests is to correctly simulate and model quench front phenomena such as entrainment, the focus of second-tier scaling is to correctly model and scale quench front phenomena for a particular test facility. In order to achieve this method of scaling, the Zuber [1] methodology for preserving characteristic time ratios for the transfer and system response processes (i.e. vapor generation and entrainment) is used in this analysis. A Lagrangian control volume around the quench front is used to develop the time scales for the transfer process (heat transfer) and the system response processes (liquid, entrained, and vapor flow). This control volume analysis provides one with the ability to relate quench front phenomena from a prototypical design to a significantly different geometry and/or flow configuration. By preserving these characteristic time ratios, the phenomena that characterize the entrainment processes can be replicated to allow entrainment

experimentation in configurations with different geometries, flow rates, stored energy, and/or heat rates. The flexibility of obtaining data over a range of conditions and geometries will assist the experimenter in developing a more physical-based means of modeling quench front phenomena such as entrainment.

CONTROL VOLUME ANALYSIS AND ASSUMPTIONS

A control volume is developed at the quench front, as shown in Figure 1. The basis for the size and dimensions of the control volume is discussed following the description of the assumptions and the basis for the energy balance. Performing an energy balance on the fluid in the control volume at the quench front gives:

$$\Delta Q_{cv} = Q_{q,r} + Q_{DH} + Q_{m,in} - Q_{m,out} \quad \{1\}$$

(1) (2) (3) (4) (5)

where:

Term 1: Change in energy within the quench front control volume.

Term 2: Energy to the fluid mixture due to stored energy release from rod quench.

Term 3: Energy to the fluid mixture due to decay heat power.

Term 4: Energy of fluid entering the control volume.

Term 5: Energy of fluid mixture exiting the control volume.

FIGURE 1
LAGRANGIAN QUENCH FRONT CONTROL VOLUME

The assumptions used in this analysis are:

- The control volume is defined as encompassing the fluid region at and below the quench front where the most of the stored energy release to the fluid is occurring.
- Decay heat power, term 3 in Equation {1}, is negligible within the quench front control volume. Based on calculations performed on the FLECHT-SEASET rod bundle geometry [4], stored energy release is approximately two orders of magnitude more than decay heat power contributions at the quench front. Decay heat power contributions below the quench front are taken into account by using a specified control volume inlet quality.
- No axial or azimuthal conduction in the rod region to the outside of the control volume. Conduction within the control volume is modeled using the concept of "thermal wave penetration" as shown in Figure 2.
- Saturation conditions exist within the quench front control volume. The vapor void fraction is calculated as a function of the Martinelli parameter using the local quality and fluid conditions [5]. Saturated quench front conditions are characteristic of the low flooding rate FLECHT-SEASET experiments [4]. This assumption implies that no droplet evaporation is assumed to occur in the quench front control volume.
- Vapor and liquid flow is upward. Top flooding is not considered in this analysis.
- Non-condensable gases are not considered. This assumption is reasonable since, in a PWR reflood scenario, most non-condensable gases have been driven out of the control volume by the time at which the peak representative clad temperature occurs.
- All entrainment occurs in the quench front control volume. This assumption is valid for low flooding rate cases in which inverted annular film boiling does not exist. No entrainment is assumed to occur below the quench front.
- Prior to quench, the rod temperature distribution is uniform. This assumption is valid due to the low Biot number characteristic heat transfer in regions above the quench front, neglecting the effects of axial conduction.
- The flow exiting the control volume is in the form of droplets and vapor. Continuous liquid is assumed to exist at or below the quench front. (i.e. flooding rate is low enough that inverted annular film boiling does not exist)

- The rod region is modeled as a continuous homogeneous material reflecting the effects of stored energy. Volume-averaged material properties may be used for approximations of different configurations.
- Mass accumulation is assumed not to occur within the quench front control volume.

FIGURE 2
CONTROL VOLUME THERMAL WAVE PENETRATION – VIEW OF THERMAL WAVE WITHIN THE CONTROL VOLUME ROD

Based on the transient conduction analysis presented by Kreith and Bohn [6], a thermal change that is suddenly imposed on a surface, such as that characterized by quench front propagation, will cause a temperature wave to be propagated by conduction within the solid. The propagation of the thermal wave through the rod is subsequently used in this analysis to determine the height, Δz , of the control volume. The thermal wave is defined as the distance beyond which, for all practical purposes, there is no heat flow [7].

At the bottom of the quench front control volume, the thermal wave is assumed to have penetrated the entire radius of the rod, δ_r . At the top of the control volume where the quench front is located, the thermal wave will have just begun to penetrate the surface of the rod. This thermal wave propagation is seen in Figure 2. In order to provide closure for the thermal wave relationship to the control volume height, the thermal wave penetration [7] can further be described by the control volume residence time, τ_{RC} , and the volume averaged thermal diffusivity of the rod, α_r :

$$\delta_r \approx (\alpha_r \tau_{RC})^{1/2} \quad \{2\}$$

By manipulating Equation {2}, the fluid residence time, τ_{RC} , for the respective wave penetration within the control volume is expressed as:

$$\tau_{RC} \approx \frac{\delta_r^2}{\alpha_r} \quad \{3\}$$

The use of this thermal wave concept allows one to develop a relationship for a characteristic control volume height over which the quench front heat release and entrainment phenomena occur. Therefore, the stored energy within the rod is released to the control volume of height, Δz , during the residence time τ_{RC} . The characteristic control volume height, Δz , for where this energy release occurs to the fluid over the calculated residence time can subsequently be expressed as a function of the relative quench front velocity with respect to the rod, and the residence time within the control volume:

$$\Delta z = U_q \tau_{RC} = U_q \frac{\delta_r^2}{\alpha_r} \quad \{4\}$$

U_q – Quench front velocity relative to the rod (The Lagrangian control volume is moving through space with a velocity of U_q which is relative to the fixed coordinate system of the rod).

ANALYSIS OF THE CONTROL VOLUME ENERGY EQUATION

With the quench front control volume dimensions quantified using the thermal wave propagation concept and assumptions from Section 2, each term of the control volume energy balance (Equation {1}) for the fluid at the quench front is separately characterized and presented in the following portions of this section.

Term 1 of Equation {1}:

$$\Delta Q_{cv} = \Delta z A_x \frac{d}{dt} (\rho_m e_m) = \Delta z A_x \frac{d}{dt} \left(\alpha \rho_g e_g + \{1 - \alpha\} \rho_f e_f \right) \quad \{5\}$$

A_x is the cross sectional flow area representing a thermal hydraulic cell for a given rod.

Δz is the control volume height.

α is the vapor void fraction.

ρ is the density, and e is the specific internal energy, where the subscripts, m, f, and g represent the mixture, fluid, and vapor, respectively.

By making the assumption that pressure is constant with time, the density and specific internal energy within the differential expression in Equation {5} will not change with time. And, since a Lagrangian perspective is employed for modeling the quench front control volume, vapor void fraction, α , will not vary with time, therefore:

$$\Delta Q_{cv} = 0 \quad \{6\}$$

Term 2 of Equation {1}:

Based on the thermal wave propagation assumption presented in the previous section, it is assumed that the stored energy within the rod bordering the control volume of height, Δz , is released to the coolant during the residence time.

$$Q_{q,r} = \int_{z_1}^{z_2} \bar{q}_r' dz \quad \{7\}$$

$\bar{q}_r'$ is the average rod linear heat rate due to quenching.

Accounting for the linear heat rate over time, Equation {7} is written as:

$$\int_{z_1}^{z_2} \bar{q}_r' dz = \frac{\int_{z_1}^{z_2} \int_{t_1}^{t_2} q_r'(t) dt dz}{\int_{t_1}^{t_2} dt} \quad \{8\}$$

At the time of quench, an initial uniform rod temperature can be assumed upstream of the quench front since heat transfer prior to the time of quench is characterized by a very low heat transfer coefficient that results in a Biot number less than 0.1. Therefore, the total linear energy rate released from the rod during the control volume residence time is expressed as:

$$\int_{t_1}^{t_2} q_r'(t) dt = \pi \rho_r c_{p,r} \delta_r^2 (T_{rod} - T_{sat}) \quad \{9\}$$

δ_r is the effective thermal penetration depth given by Equation {2}, which is assumed to be equal to the radius of the rod for this case.

Equation {9} is substituted into Equation {8}, and the remaining integrations are carried out resulting in a Δz in the numerator and a Δt in the denominator. From the Lagrangian perspective, the quench front velocity with respect to the rod is expressed as a function of the result of these integrations:

$$\frac{(z_2 - z_1)}{(t_2 - t_1)} = U_q \quad \{10\}$$

Operating on Equation {8}, by performing the integrations over time and space, and the substitution of the quench front velocity term results in:

$$Q_{q,r} = \pi \rho_r c_{p,r} \delta_r^2 (T_{rod} - T_{sat}) U_q \quad \{11\}$$

Term 4 of Equation {1}:

The relationship for the energy of the mixture entering the Lagrangian quench front control volume is given by:

$$Q_{m,in} = \hat{w}_{f,in} h_f + \hat{w}_{g,in} h_g \quad \{12\}$$

$\hat{w}_{f,in}$ is the Lagrangian liquid mass flow rate into the control volume (assuming a frame of reference moving with the control volume)

$\hat{w}_{g,in}$ is the Lagrangian vapor mass flow rate into the control volume (assuming a frame of reference moving with the control volume)

h is the enthalpy, where the subscripts f and g denote the fluid and vapor, respectively.

The control volume inlet flow is assumed to be a mixture of saturated liquid and vapor, at a given quality, x_{in} . The velocity of the liquid entering the Lagrangian quench front control volume can be expressed as a function of the test section inlet mass flow rate, the vapor void fraction, and the quench front velocity, for a velocity relative to the fixed frame of the test section:

$$U_{f,in} = \frac{(1 - x_{in}) w_{in}}{(1 - \alpha_{in}) \rho_f A_x} - U_q \quad \{13\}$$

w_{in} is the Eulerian test section inlet mass flow rate relative to the fixed fuel rod
 x_{in} is the vapor quality entering the quench front control volume
 α_{in} is the vapor void fraction at the inlet to the control volume

Similarly, the velocity of the vapor entering the Lagrangian quench front control volume can be expressed as a function of the test section inlet mass flow rate, the vapor void fraction, and the quench front velocity:

$$U_{g,in} = \frac{x_{in} w_{in}}{\alpha_{in} \rho_f A_x} - U_q \quad \{14\}$$

The Lagrangian mass flow rate of the liquid entering the control volume is expressed in terms of Eulerian quantities as:

$$\hat{w}_{f,in} = U_{f,in} (1 - \alpha_{in}) \rho_f A_x = (1 - x_{in}) w_{in} - U_q (1 - \alpha_{in}) \rho_f A_x \quad \{15\}$$

Similarly, the Lagrangian mass flow rate of the vapor entering the control volume is expressed in terms of Eulerian quantities as:

$$\hat{w}_{g,in} = U_{g,in} \alpha_{in} \rho_g A_x = x_{in} w_{in} - U_q \alpha_{in} \rho_g A_x \quad \{16\}$$

The void fraction can be estimated using the quality and the local fluid properties using the relationship between void fraction and the Martinelli parameter, X , as proposed by Wallis [5]:

$$\alpha = (1 + X^{0.8})^{-3.78} \quad \{17\}$$

The Martinelli parameter is defined by:

$$X = \sqrt{\left(\frac{1-x}{x}\right)^{1.75} \left(\frac{\rho_g}{\rho_f}\right) \left(\frac{\mu_f}{\mu_g}\right)^{0.25}} \quad \{18\}$$

A final expression for the energy of the mixture entering the Lagrangian quench front control volume is obtained by substituting Equations {15} and {16} into Equation {12}:

$$Q_{m,in} = ((1 - x_{in}) w_{in} - U_q (1 - \alpha_{in}) \rho_f A_x) h_f + (x_{in} w_{in} - U_q \alpha_{in} \rho_g A_x) h_g \quad \{19\}$$

By collecting terms, Equation {19} simplifies to:

$$Q_{m,in} = (1 - x_{in})w_{in}h_f + x_{in}w_{in}h_g - [(1 - \alpha_{in})\rho_f h_f + \alpha_{in}\rho_g h_g]A_x U_q \quad \{20\}$$

Term 5 of Equation {1}:

Since the flow exiting the control volume is assumed to be in the form of droplets and vapor at saturation temperature, the term representing the energy of the mixture exiting the control volume is expressed as:

$$Q_{m,out} = \hat{w}_{e,out}h_f + \hat{w}_{g,out}h_g \quad \{21\}$$

$\hat{w}_{e,out}$ is the Lagrangian entrained droplet flow rate exiting the control volume.

$\hat{w}_{g,out}$ is the Lagrangian vapor flow rate exiting the control volume.

Using the Lagrangian quench front model, assuming that all entrainment is generated within the quench front control volume, and assuming no mass collection within the quench front control volume, the entrained flow rate exiting the control volume is expressed as the entrainment rate at the quench front:

$$\hat{w}_{e,out} = w_{e,gen} \quad \{22\}$$

$w_{e,gen}$ is the control volume liquid droplet entrainment rate

The vapor flow rate exiting the control volume is expressed as the sum of the vapor generation rate at the quench front, and the rate at which vapor enters the control volume given by Equation {18}.

$$\hat{w}_{g,out} = w_{g,gen} + \hat{w}_{g,in} = w_{g,gen} + x_{in}w_{in} - U_q \alpha_{in} \rho_g A_x \quad \{23\}$$

$w_{g,gen}$ is the control volume vapor generation rate

By substituting the entrained and vapor flow rate terms from Equations {22} and {23} into Equation {21}, the energy of the mixture exiting the control volume is written as:

$$Q_{m,out} = w_{e,gen}h_f + (x_{in}w_{in} - U_q \alpha_{in} \rho_g A_x)h_g + w_{g,gen}h_g \quad \{24\}$$

Combined Equation for the Energy Balance in the Lagrangian Control Volume:

By substituting Equations {6}, {11}, {20}, and {24} into Equation {1} and assuming that decay heat power contributions to quench front heat transfer are minor, Equation {1} is rewritten as:

$$\pi \rho_r c_{p,r} \delta_r^2 (T_{rod} - T_{sat}) U_q + (1 - x_{in}) w_{in} h_f + x_{in} w_{in} h_g - [(1 - \alpha_{in}) \rho_f h_f + \alpha_{in} \rho_g h_g] A_x U_q = w_{e,gen} h_f + (x_{in} w_{in} - U_q \alpha_{in} \rho_g A_x) h_g + w_{g,gen} h_g \quad \{25\}$$

The inlet vapor energy terms in Equation {25} can be cancelled to result in the combined energy balance equation for the Lagrangian quench front control volume as:

$$\pi \rho_r c_{p,r} \delta_r^2 (T_{rod} - T_{sat}) U_q + (1 - x_{in}) w_{in} h_f - [(1 - \alpha_{in}) \rho_f h_f] A_x U_q = w_{e,gen} h_f + w_{g,gen} h_g \quad \{26\}$$

(It is interesting to note that through this analysis, the energy balance on the quench front control volume is not dependent on the quench front height, Δz)

Mass Balance at the Quench Front

The use of the Lagrangian quench front control volume has yielded an expression for relating vapor generation at the quench front and rod energy release at the quench front in terms of the relative velocity between the quench front and the rod. The calculation of the entrainment at the quench front required the determination of the vapor generation in the Lagrangian quench front control volume and quench velocity. The entrainment rate calculation at the quench front is conducted by assuming the quench front to be a "plane." A subsequent mass balance across the plane of the quench front is conducted to provide closure.

Assuming that the vapor generated at the quench front and the vapor produced below the quench front both contribute to the entrainment occurring at the quench front, the entrainment can be estimated using the entrainment correlation in the COBRA-TF computer code [8] that is given as:

$$w_{e,gen} = \left(\frac{\alpha U_g}{U_{crit}} \right)^2 w_g \quad \{27\}$$

where U_g is the vapor velocity at the quench front.

U_{crit} is the critical entrainment vapor velocity for the fixed frame of the test section (Eulerian) described by:

$$U_{crit} = \left(\frac{4We_{d,crit}}{3C_D} \right)^{0.25} \left(\frac{\sigma g \Delta \rho}{\rho_g^2} \right)^{0.25} \quad \{28\}$$

where $We_{d,crit}=2.0$ and $C_D=0.45$ for the COBRA-TF model [8].

Assuming that the void distribution at the quench front can be represented by a bulk value, α , the Eulerian vapor velocity at the quench front is given as:

$$U_g = \frac{w_g}{\rho_g A_x \alpha} \quad \{29\}$$

Furthermore, assuming that all of the entrainment occurs at the plane of the quench front and is a result of the vapor generated both at and below the quench front, Equation {29} is substituted into Equation {27} resulting in the following expression for the entrainment rate that is a function of vapor flow rate, density, flow area, and critical velocity:

$$w_{e,gen} = \left(\frac{1}{\rho_g A_x U_{crit}} \right)^2 w_g^3 = \left(\frac{1}{\rho_g A_x U_{crit}} \right)^2 (w_{g,gen} + x_{in} w_{in})^3 \quad \{30\}$$

By performing a fluid mass balance through the plane of the quench front and using the result of Equation {30}, the quench front velocity relative to the rod can be expressed in terms of the inlet flow rate, vapor generation rate, the flow area, density, and critical vapor velocity:

$$U_q = \frac{w_{in} - x_{in} w_{in} - w_{g,gen} - w_{e,gen}}{(1 - \alpha_{in}) \rho_f A_x} = \frac{(1 - x_{in}) w_{in} - w_{g,gen} - \left(\frac{1}{\rho_g A_x U_{crit}} \right)^2 (w_{g,gen} + x_{in} w_{in})^3}{(1 - \alpha_{in}) \rho_f A_x} \quad \{31\}$$

Continuing with the thermal wave propagation concept for modeling of the quench front control volume, and assuming that all the heat transfer takes place in the quench front control volume results in vapor generation due to the liquid being at saturation temperature, the energy release and vapor generation rate are equated as:

$$w_{g,gen} h_{fg} = \pi \rho_r c_{p,r} \delta_r^2 (T_{rod} - T_{sat}) U_q \quad \{32\}$$

By solving for quench front velocity with respect to the rod, U_q , in Equation {32} and equating the result to Equation {31}, the following expression is arrived at which permits one to solve for the vapor generation rate as:

$$U_q = \frac{w_{g,gen} h_{fg}}{\pi \rho_r c_{p,r} \delta_r^2 (T_{rod} - T_{sat})} = \frac{(1 - x_{in}) w_{in} - w_{g,gen} - \left(\frac{1}{\rho_g A_x U_{crit}} \right)^2 (w_{g,gen} + x_{in} w_{in})^3}{(1 - \alpha_{in}) \rho_f A_x} \quad \{33\}$$

Using the Wallis relationship between the Martinelli parameter and the void fraction, Equations {17} and {18} can be manipulated to provide the following relationship between vapor void fraction and quality as:

$$\alpha_{in} = \left[1 + \left\{ \left(\frac{1 - x_{in}}{x_{in}} \right)^{1.75} \left(\frac{\rho_g}{\rho_f} \right) \left(\frac{\mu_f}{\mu_g} \right)^{0.25} \right\}^{0.4} \right]^{-0.378} \quad \{34\}$$

The vapor void fraction dependency is subsequently eliminated by substituting Equation {34} into Equation {33} giving:

$$U_q = \frac{w_{g,gen} h_{fg}}{\pi \rho_r c_{p,r} \delta_r^2 (T_{rod} - T_{sat})} = \frac{\left\{ (1 - x_{in}) w_{in} - w_{g,gen} - \left(\frac{1}{\rho_g A_x U_{crit}} \right)^2 (w_{g,gen} + x_{in} w_{in})^3 \right\}}{\left(1 - \left[1 + \left\{ \left(\frac{1 - x_{in}}{x_{in}} \right)^{1.75} \left(\frac{\rho_g}{\rho_f} \right) \left(\frac{\mu_f}{\mu_g} \right)^{0.25} \right\}^{0.4} \right]^{-0.378} \right) \rho_f A_x} \quad \{35\}$$

(Note: Consistent with the quench front control volume energy balance, calculated quench front velocity is independent of control volume height.)

Using the given rod configuration/prototypical dimensions, material properties, test conditions, inlet flow rate, and vapor quality below the quench front, Equation {35} can be iteratively solved for the vapor generation rate. After determining the vapor generation rate, the entrainment rate is calculated using Equation {30} thereby allowing the scaling Pi groups to be evaluated.

PI GROUP DEVELOPMENT

Zuber, et al. [1] developed a scaling methodology that is based on the hierarchy for characteristic temporal scales within a control volume. Two classes of temporal scales are delineated: one is associated with system response, and the other is associated with a particular transfer process. For a given control volume, V , and volumetric filling rate, $\dot{V}$, the system response is characterized by the residence time within the control volume of height Δz . By equating this to the Lagrangian quench front control volume modeled in this scaling study, and setting the average density to the fluid density as a reference point (a valid assumption since the mixture below the quench front generally has a low quality), the flow residence time in the control volume, τ_{flow} , can be expressed as:

$$\tau_{flow} = \frac{V}{\dot{V}_{in}} = \frac{\rho_f A_x \Delta z}{w_{in}} \quad \{36\}$$

Equation {36} is expressed as a frequency, which is simply the reciprocal of the residence time:

$$\omega_{flow} = \frac{1}{\tau_{flow}} \quad \{37\}$$

Similarly, the vapor residence time, τ_{vap} , and an entrained droplet residence time, τ_{entr} , can be expressed as:

$$\tau_{vap} = \frac{V}{\dot{V}_{vap}} = \frac{\rho_g A_x \Delta z}{(w_{g,gen} + x_{in} w_{in})} \quad \{38\}$$

$$\tau_{entr} = \frac{V}{\dot{V}_{entr}} = \frac{\rho_f A_x \Delta z}{w_{e,gen}} \quad \{39\}$$

As discussed by Zuber, et al. [1], each transfer process within a control volume is characterized by a rate and by a transfer area. The property being transferred can be mass, momentum, energy, etc. In order to obtain an expression for the temporal scale associated with a parameter such as rod heat transfer within the quench front control volume, the quench front rod heat transfer time constant must be evaluated.

Incropera and DeWitt [9] present an approximate solution to the transient one-dimensional conduction solution for an infinite cylinder of radius, r_o . Assuming that the rod is at a uniform initial temperature, T_i , and is immersed into a fluid at T_{inf} , the resulting transient temperature distribution solution is presented in the form of an infinite

series. Using the first term of the infinite series as an approximate solution, Incropera and Dewitt [9] arrive at the dimensionless temperature distribution approximated by:

$$\vartheta^* = C_1 e^{-\zeta_1^2 Fo} \cos(\zeta_1 r^*) \quad \{40\}$$

ϑ^* = the dimensionless temperature

ζ_1 = solution coefficient which is a function of the Biot number

C_1 = solution coefficient which is a function of the Biot number

Fo = the Fourier number

r^* = the dimensionless location

The overall temperature dependency as a function of time is expressed by the exponential term in Equation {40}. The rod heat transfer time constant and frequency from the exponential expression is given by:

$$\tau_{rod} = \frac{t}{\zeta_1^2 Fo} = \frac{r_o^2}{\zeta_1^2 \alpha_r} \quad \{41\}$$

$$\omega_{rod} = \frac{1}{\tau_{rod}} \quad \{42\}$$

where:

$$\alpha_r = \frac{k_r}{\rho_r c_{p,r}} \quad \{43\}$$

ζ_1 is obtained from the summary of constants for the transient conduction solution given in Reference [9], as a function of the Biot number (Bi). The Biot number is expressed as:

$$Bi = \frac{h_{trans} \delta_r}{k_r} \quad \{44\}$$

The transition boiling heat transfer coefficient, h_{trans} , must be assumed for the case of this quench front control volume analysis. This quantity can be feasibly approximated based on the results of the FLECHT experiments [4].

Zuber, et al. [1] define a characteristic time ratio that represents the total change of a reference quantity (for example: rod stored energy) in a control volume during the residence time τ_{cv} , brought about by a specific heat transfer process (for example: heat transfer by convection). In this quench front control volume analysis, the rod stored

energy release characteristic frequency is represented by ω_{rod} (Equation {42}), and the respective control volume residence times are described in Equations {36}, {38}, and {39}.

In the study of a complex process such as quench front energy release, the designer attempts to optimize the similitude for the processes of greatest interest [1]. For the quench front control volume case, it is postulated that the rod energy release into the coolant is the most important process to maintain.

This process can be scaled with the following Pi groups that relate the quench front energy release and the flow, vapor, and entrained residence times within the control volume as ratios of the characteristic time scales:

$$\Pi_1 = \omega_{rod} \tau_{flow} \quad \{45\}$$

$$\Pi_2 = \omega_{rod} \tau_{vap} \quad \{46\}$$

$$\Pi_3 = \omega_{rod} \tau_{entr} \quad \{47\}$$

For a specific transfer process such as the quench front energy release to have the same effects in the prototype (p) and the laboratory scale model (m), then the characteristic time ratio [1] must be preserved, thus:

$$[\Pi_x]_p = [\Pi_x]_m \quad \{48\}$$

The effect of the distortion between the model and the prototypical design is quantified and evaluated by:

$$D_x = \frac{[\Pi_x]_p - [\Pi_x]_m}{[\Pi_x]_p} \quad \{49\}$$

SCALING COMPARISON

A sample set of scaling calculations has been performed to demonstrate the use of these newly developed Pi groups for the modeling, replication, and scaling of quench front-related phenomena. Scaling Pi groups one through three {Equations 45, 46, and 47} are calculated, using the quench front scaling methodology developed in this report, for a prototypical Westinghouse 17 x 17 fuel design and the heater rod design employed in the FLECHT SEASET [4] series of reflood experiments. The Pi groups were calculated for conditions at 40 psia, with a 1.0 inch per second cold fill flow rate, and are plotted as a function of mixture quality at the quench front in Figures 3, 4, and 5.

FIGURE 3
 Π_1 (TOTAL FLOW GROUP) AS A FUNCTION OF MIXTURE QUALITY

FIGURE 4
 Π_2 (VAPOR FLOW GROUP) AS A FUNCTION OF MIXTURE QUALITY

FIGURE 5
 Π_3 (ENTRAINED FLOW GROUP) AS A FUNCTION OF MIXTURE QUALITY

From the plots of the quench front-related scaling groups (Figures 3, 4, and 5), it is evident that there is roughly a factor of two distortion in the scaling of quench front phenomena when comparing a prototypical Westinghouse PWR fuel assembly design and the heater rod design used in the PWR FLECHT SEASET [4] experiments at the same cold fill rate and pressure conditions. This distortion is primarily attributed to the significant difference in thermal conductivity between the prototypical fuel design, and that of the boron nitride heater rods used in the FLECHT SEASET experiments. The significantly higher thermal conductivity of the boron nitride, as compared to a uranium dioxide fuel pellet, results in a much more rapid quench front heat release in the FLECHT heater rod design, thereby creating a distortion in quench front related phenomena.

In an effort to show how the test parameters can be adjusted to remove distortions in the quench front related entrainment phenomena, a sample calculation of Π_3 (entrainment related scaling group) has been performed for a postulated FLECHT cold fill rate of 1.0 inches per second, and a Westinghouse 17 x 17 cold fill rate of 2.5 inches per second. These results are presented in Figure 6, and show a better preservation of the quench front related entrainment phenomena. This result shows that though there may be differences between a prototypical and experimental design, experimental parameters can be varied so as to maintain and preserve quench front related phenomena such as droplet entrainment for a given set of prototypical conditions.

FIGURE 6
USE OF DIFFERENT COLD FILL RATES TO REMOVE DISTORTIONS IN Π_3

CONCLUSIONS

A set of scaling Π groups related to the quench front phenomena have been developed based on an energy balance on a quench front fluid control volume that is characterized by conduction-based thermal wave propagation within a rod undergoing quenching and subsequently transferring heat to the control volume. The underlying assumptions within the quench front control volume include the assumption that saturation conditions exist, that the decay heat power contribution is small relative to the stored energy, and that all entrainment occurs at the quench front. The scaling Π groups (Π_1 through Π_3) relate the characteristic time for the quench front energy release with the characteristic time for flow, vapor, and entrained residence time within the control volume using the methodology presented by Zuber, et al. [1]. By matching the scaling Π group that is related to the quench front phenomena (i.e. total flow, vapor generation, or entrainment) to be studied for both a laboratory-scale model and a prototypical design, preservation of the quench front energy release with respect to the specific phenomenon (i.e. entrainment process) can be maintained.

The exit vapor flow rate can be calculated utilizing an iterative manner. This is required due to the third order polynomial expression that was developed (Equation {35}). This determination of exit vapor flow rate permits an estimate of the quench front velocity, a parameter that has usually been assumed in previous scaling studies.

Since flow quality is a boundary condition for the saturated flow entering the quench front control volume, this quality must be specified for the scaling analysis. This quality can be readily determined for a given quench front location, decay heat power level, inlet flow rate, and inlet subcooling by integrating the heat flux below the quench front location.

An important benefit of the scaling pi groups developed in this study is that they make it possible to construct a laboratory scale model using different materials and geometric configurations than the prototype, while preserving the important entrainment phenomena. Preservation of the quench front phenomena can allow the test facility design to have the requisite instrumentation to make more-accurate measurements while not being limited by the need to replicate prototypical dimensions and materials. For example, a test facility can be designed so that it can be fitted with windows to observe droplets and entrainment phenomena such that measurements can be performed on droplet size and velocity. Such a reflood facility could be better designed to hold system pressure, allowing higher pressures to be analyzed with less need for elaborate support structures. Due to the design flexibility in preserving quench front-related phenomena using these methods, there can be a realized benefit in allowing experiments to be run over a wider range of temperature and pressure conditions, along with the concomitant benefit of financial savings due to the ability to mount instrumentation and support the test section. With the ability to perform inverse conduction calculations, measure droplet size distributions, and perform mass and energy balances, quench front phenomena can be better quantified allowing more comprehensive physical models to be developed for calculating the quench front and entrainment heat transfer characteristics during a postulated reflood case.

NOMENCLATURE

- A_x - cross sectional flow area representing a thermal hydraulic cell for a given rod (m^2).
- Bi - Biot number.
- C_D - droplet drag coefficient.
- $c_{p,r}$ - volume-averaged rod specific heat ($J/kg \cdot K$).
- D_x - distortion between model and prototypical design.
- e - specific internal energy (J/kg).
- g - gravitational acceleration (m/s^2).
- h - enthalpy (J/kg).
- h_{trans} - transition boiling heat transfer coefficient ($W/m^2 \cdot K$)
- k - thermal conductivity ($W/m \cdot K$)
- ΔQ_{cv} - change in energy within the quench front control volume (J).
- $Q_{q,r}$ - energy to the fluid mixture due to stored energy release from rod quench (J).
- Q_{DH} - energy to the fluid mixture due to decay heat power (J).
- $Q_{m,in}$ - energy of fluid entering the control volume (J).
- $Q_{m,out}$ - energy of fluid mixture exiting the control volume (J).

$\bar{q}_r$ - average rod linear heat rate due to quenching (W/m).
 r_o - rod radius (m).
 T_{rod} - average rod temperature (K).
 T_{sat} - saturation temperature (K).
 U_{crit} - critical vapor velocity used in the COBRA-TF entrainment correlation (m/s).
 $U_{f,in}$ - Lagrangian velocity of liquid entering the quench front control volume (m/s).
 U_g - quench front vapor velocity used in the COBRA-TF entrainment correlation (m/s).
 $U_{g,in}$ - Lagrangian velocity of vapor entering the quench front control volume (m/s).
 U_q - Eulerian quench front velocity relative to the fixed fuel rod (m/s).
 V - volume of quench front control volume (m³).
 $\dot{V}$ - volumetric flow rate (m³/s).
 $We_{d,crit}$ - critical droplet Weber number used in COBRA-TF entrainment correlation.
 $w_{e,gen}$ - control volume liquid droplet entrainment rate (kg/s).
 $\hat{w}_{e,out}$ - Lagrangian entrained droplet flow rate exiting the control volume assuming a frame of reference moving with the control volume (kg/s).
 $\hat{w}_{f,in}$ - Lagrangian liquid mass flow rate into the control volume assuming a frame of reference moving with the control volume (kg/s).
 $\hat{w}_{g,in}$ - Lagrangian vapor mass flow rate into the control volume assuming a frame of reference moving with the control volume (kg/s).
 $w_{g,gen}$ - control volume vapor generation rate (kg/s).
 $\hat{w}_{g,out}$ - Lagrangian vapor flow rate exiting the control volume assuming a frame of reference moving with the control volume (kg/s).
 w_{in} - Eulerian test section inlet mass flow rate relative to the fixed fuel rod (kg/s).
 X - Martinelli parameter.
 x_{in} - the vapor quality entering the quench front control volume.
 Δz - control volume height (m).

Greek Letters

α - vapor void fraction.
 α_{in} - vapor void fraction at the inlet to the quench front control volume.
 α_r - rod thermal diffusivity (m²/s).
 δ_r - rod thermal penetration length (m).
 σ - surface tension (N-m).
 ρ - density (kg/m³).
 $\Delta\rho = \rho_f - \rho_g$ (kg/m³).
 τ_{entr} - control volume entrained droplet residence time (s).
 τ_{flow} - control volume flow residence time (s).
 τ_{RC} - control volume fluid residence time (s).

τ_{rod} - rod thermal time constant (s).

τ_{vap} - control volume vapor residence time (s).

ω_{rod} - frequency of rod thermal release (1/s).

Subscripts

f – fluid

g – vapor

m – mixture

r – rod

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