A SCALING LAW VERIFICATION OF THE DELFT SIMULATED REACTOR (DESIRE)

B.T. Adams
Interfaculty Reactor Institute, Delft University of Technology
Mekelweg 15, 2629 JB Delft, the Netherlands
e-mail: adams@iri.tudelft.nl

ABSTRACT

The Interfaculty Reactor Institute (IRI) is studying the fundamental parameters that drive the natural circulation flow core cooling concept that is incorporated in many advanced BWR designs with the DElft SImulated REactor, or DESIRE. This electrically-powered, freon-cooled, two-phase flow loop is an exact scaled replica of a single fuel assembly of the Netherlands' Dodewaard reactor, which used natural circulation for core cooling in normal operation. The water-to-freon scaling law analysis that was used in the design of DESIRE was based upon a simple one-dimensional drift flux model and was never independently verified. The commercial thermal hydraulic code MONA, which contains an advanced two fluid model, was recently added to the suite of analysis tools that are available at IRI. Thus, the addition of MONA allowed IRI to verify the ideal scaling law criteria that were derived based on the simpler drift flux model. This verification also revealed that the fuel rod pitch to diameter ratio of the actual scaled DESIRE facility deviates from an ideal scaled Dodewaard facility, and allowed the effect of this design distortion to be quantified. Finally, the MONA model of the actual DESIRE facility was benchmarked against experimentally measured axial void profiles. This paper describes the results of the DESIRE water-to-freon scaling law analysis verification and the MONA benchmarking activities.

I. INTRODUCTION

Passive safety features are an essential characteristic of advanced reactor designs. The use of natural circulation as the reactor coolant technique, rather than forced circulation using pumps, is thus incorporated in many of these design concepts. The fundamental parameters that determine the natural circulation flow are not well known, however. This phenomenon was previously studied by the Interfaculty Reactor Institute (IRI) at the Dodewaard reactor, which was the only operating reactor in the western world that used natural circulation core cooling (the reactor was shutdown in March of this year). Experimental measurements at the reactor were limited, however, by a lack of instrumentation and the inaccessibility imposed by power operation. The DESIRE facility was thus designed and constructed to allow detailed measurements of the parameters that influence natural circulation reactor cooling.

DESIRE is an electrically-powered, freon-cooled, two-phase flow loop that represents a scaled version of the Dodewaard reactor with a single fuel assembly.[1] The decision to use electrical power for heat generation precluded the use of water as a coolant (due to its high latent heat of vaporization), so freon-12 (CF_2Cl_2) was selected as a logical alternative.[2] The use of freon as the coolant also allowed the facility to be operated at a much lower pressure and temperature than the actual Dodewaard reactor. The facility had to exhibit the same operating characteristics as the actual BWR in all other respects, however, for the simulations to remain useful in the study of the fundamental natural circulation flow phenomenon. IRI thus performed a water-to-freon coolant scaling law analysis to design the DESIRE flow loop. A one-dimensional drift flux model was used in this analysis, based primarily on its simplicity relative to the alternative two-fluid model.[3] The DESIRE scaling law derivation has never been independently verified, however.

IRI recently acquired the commercial thermal hydraulic code MONA.[4] This code is a dynamic simulator for two-phase flow and heat transfer that incorporates an advanced seven-conservation equation, two-fluid model: separate equations are used to describe the mass, energy, and momentum of both the gas and liquid film phases, with a final mass equation included to treat the droplets. The code contains fluid properties for both water and freon-12 coolants. MONA can thus be used to independently verify the previous drift flux model scaling law analysis that was utilized to design the DESIRE facility. We developed MONA models of the actual freon-cooled DESIRE facility and an equivalent, full-scale, water-cooled Dodewaard assembly to perform this verification. Finally, we have compared the MONA predictions of the DESIRE void fraction distribution to the measured experimental data.

II. OVERVIEW OF THE DESIRE SCALING LAW ANALYSIS

This section provides an overview of the primary considerations and the key results of the water-to-freon scaling law analysis that was used to design the DESIRE facility. The complete derivation of the scaling criteria is fully described in the references and will not be repeated herein.[1,2] A number of dimensionless similarity groups that should be kept constant are first obtained by non-dimensionalizing the balance equations of the drift flux model. The number of similarity groups that is obtained with this approach is larger than the number of free parameters that can be adjusted in the scaled facility, however, so some compromises must be made. The similarity groups are thus separated into the primary groups, whose values must be maintained in the scaled facility, and secondary groups, whose values must simply be accepted. Since the axial void profile and flow regime transitions have a significant influence on the natural circulation flow these parameters were thus used as the primary scaling criteria. A wide variety of flow regimes are present in the Dodewaard reactor. The coolant enters the core as a subcooled liquid, whereas at the top of the core as much as 70% of the coolant volume has been turned to steam. The flow regimes present in the two-phase region thus include bubbly, slug, churn, and annular flow patterns. The scaling law derivation had to treat each of these flow regimes separately because information on the localized void fraction was required. An energy balance applied to the subcooled boiling region indicated that proper scaling of the flow quality and inlet enthalpy was obtained if the phase change and subcooling numbers were kept constant, where:

$$N_{pch} = \left(\frac{\dot{q}''}{\dot{m}''\, r}\right)\left(\frac{4l}{D_h}\right) \equiv \text{phase change number}$$

$$\mathrm{Ns} = \left(\frac{h_{\mathrm{liq}}^{\mathrm{sat}} - h_{inl}}{\mathrm{r}} \right) \equiv \text{subcooling number}.$$

where $\dot{q}''$ is the heat flux (assumed constant), $\dot{m}''$ is the mass flux, r is the latent heat of vaporization, l is the length of the rod, D_h is the hydraulic diameter of a flow channel in the assembly, and $h_{\mathrm{liq}}^{\mathrm{sat}}$ and h_{inl} are the enthalpies of the liquid at saturation and at the assembly inlet, respectively. Similarly, the non-dimensionalization of the conservation equations of the drift-flux model indicated that the proper scaling of the flow in the thermal equilibrium region was obtained by matching the dimensionless numbers:

$$N_\rho = \left(\frac{\rho_v}{\rho_{liq}} \right) \equiv \text{density number}$$

$$N_g = \left(\frac{D_h}{l} \right) \equiv \text{geometry number}$$

$$N_{Fr} = \frac{(\dot{m}'')^2}{\rho_{liq}^2 g l} \equiv \text{Froude number}$$

$$N_{pch} = \left(\frac{\dot{q}''}{\dot{m}'' r} \right) \left(\frac{4l}{D_h} \right) \equiv \left(\frac{\dot{q}''}{\dot{m}'' r} \right) \left(\frac{4}{N_g} \right)$$

$$N_{We} = \left(\frac{\dot{m}''^2 D_h}{\rho_{liq} \sigma} \right) \equiv \text{Weber number}$$

$$N_{Re} = \left(\frac{\dot{m}'' D_h}{\rho_{liq}} \right) \equiv \text{Reynolds number}$$

$$N_{Eck} = \left(\frac{\dot{m}''^2}{\rho_{liq}^2 r} \right) \equiv \text{Eckert number}$$

where ρ denotes the density, g is the acceleration due to gravity, and σ is the fluid surface tension. It was noted, however, that scaling criteria could not be derived in this manner for the bubbly flow regime where viscous effects are important, due to the lack of an appropriate fluid-to-fluid bubble development model. Thus, similarity between the water and freon cooled systems was not anticipated in this flow regime.

The decision to utilize freon-12 as a coolant predefines the operating pressure and temperature of the DESIRE facility because the dimensionless density number must be maintained. The relevant scaling criteria can then be derived using the respective fluid properties and the remaining similarity groups as shown in Table 1. Referring to the table, the size of the freon-cooled system is reduced by a factor of about two relative to the water-based system, and the power input requirement is reduced by a factor of fifty. Similarly, the required subcooling can be achieved easily with a conventional condenser. As previously stated, not all of the dimensionless numbers could be simultaneously matched. Specifically, the phase change, subcooling, geometry, density, Froude, and Weber numbers were chosen as the primary similarity groups so that the desired axial void profile and flow regime transitions

TABLE 1 - DESIRE Theoretical Scaling Parameters

parameter	dimensionless number	Dodewaard (water)	DESIRE (Freon-12)	Scaling
pressure (bars)	N_ρ	75.5	11.6	N/A
saturation temperature (°C)	N_ρ	291	48	N/A
Hydraulic Diameter (mm)	$\frac{N_{We} N_g}{N_{Fr}}$	16.9	7.77	0.4612
power (kW)	N_{pch}	1116	22.3	0.02
mass flux (kg/m²s)	N_{Fr}	1006	1137	1.135
subcooling (°C)	N_s	5	2	0.4

would be obtained, while the Reynolds and Eckert numbers were considered in the secondary similarity group. The Reynolds number scales the inertia forces to viscous forces, and is thus of interest in scaling the two-phase frictional pressure drop. It was assumed that these losses could be compensated in other portions of the system. The Eckert number scales kinetic energy transport to the latent heat and can be neglected at the low velocities expected in the DESIRE assembly.

III. THE DESIGN OF THE DESIRE FACILITY

The scaling criteria elaborated in the previous section were utilized to design and construct the DESIRE facility. The layout of the resulting two-phase flow loop is shown in Figure 1. The primary flow loop is comprised of the upper and lower downcomers, four downcomer loops, a fuel assembly, and the upper and lower risers. The secondary flow loop is comprised of the steam dome, a condenser, and an additional heat exchanger to provide supplementary cooling of the "feedwater" returned to the primary loop. The fuel assembly is composed of 35 heated rods and a single water rod arranged in a 6x6 square lattice. Three spacer elements are used to position the rods within the assembly. The spacers are scaled duplicates of the actual spacers used in the real Dodewaard reactor. The fuel rods have a cosine-shaped axial power distribution, and the heated rods can be connected individually to one of several power supplies to define any specified radial distribution. The riser provides additional driving force for the natural circulation flow. In DESIRE, the riser is composed of a fixed section and a telescoping section of equal length so that the influence of the riser length can be studied. The downcomer does not extend to the bottom of the fuel assembly as in the Dodewaard reactor, but rather is diverted into four flow loops at the top of the assembly to maximize accessibility to the heated section. A "friction control valve" is provided at the inlet of the fuel assembly to compensate for frictional losses that could not be scaled into the design of the flow loop. The downcomer and the heated assembly are equipped with two and four view ports, respectively, to allow visual observation of the flow regimes. The facility is fully instrumented (not shown in the figure) with eight thermocouples provided to measure the axial temperature variation of the coolant in the assembly. Several additional thermocouples are provided to monitor the feedwater temperature and the fluid temperature at the inlet and outlet of the downcomer, the four downcomer loops, and the riser. The system pressure is

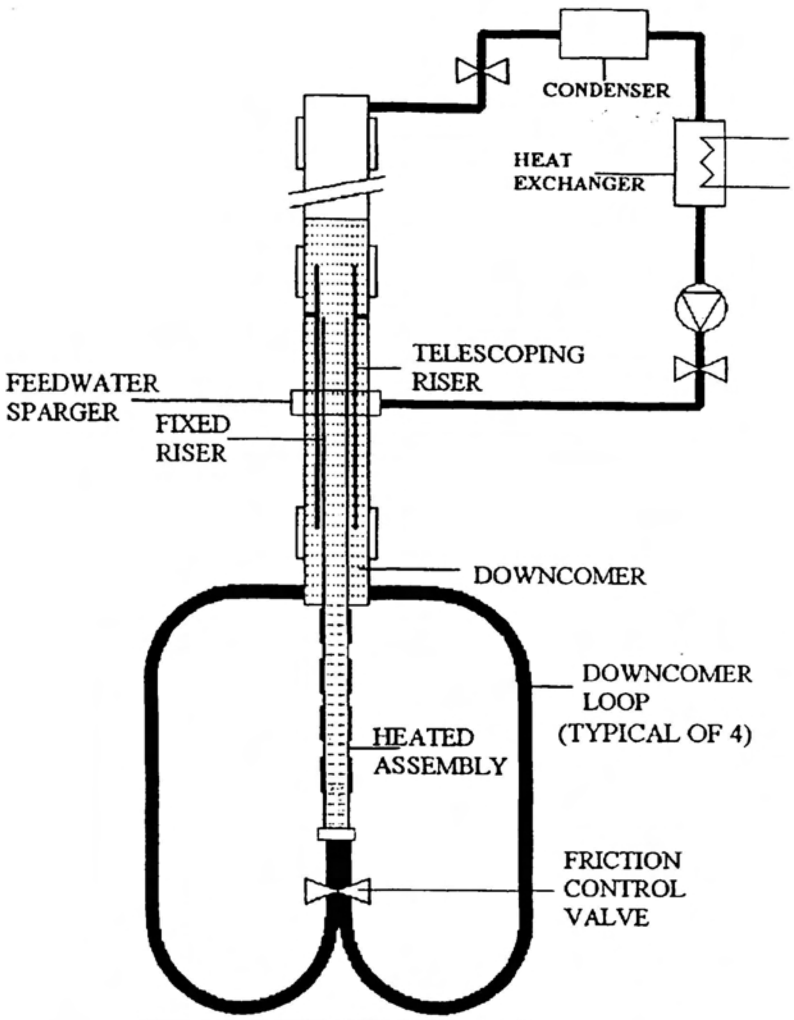


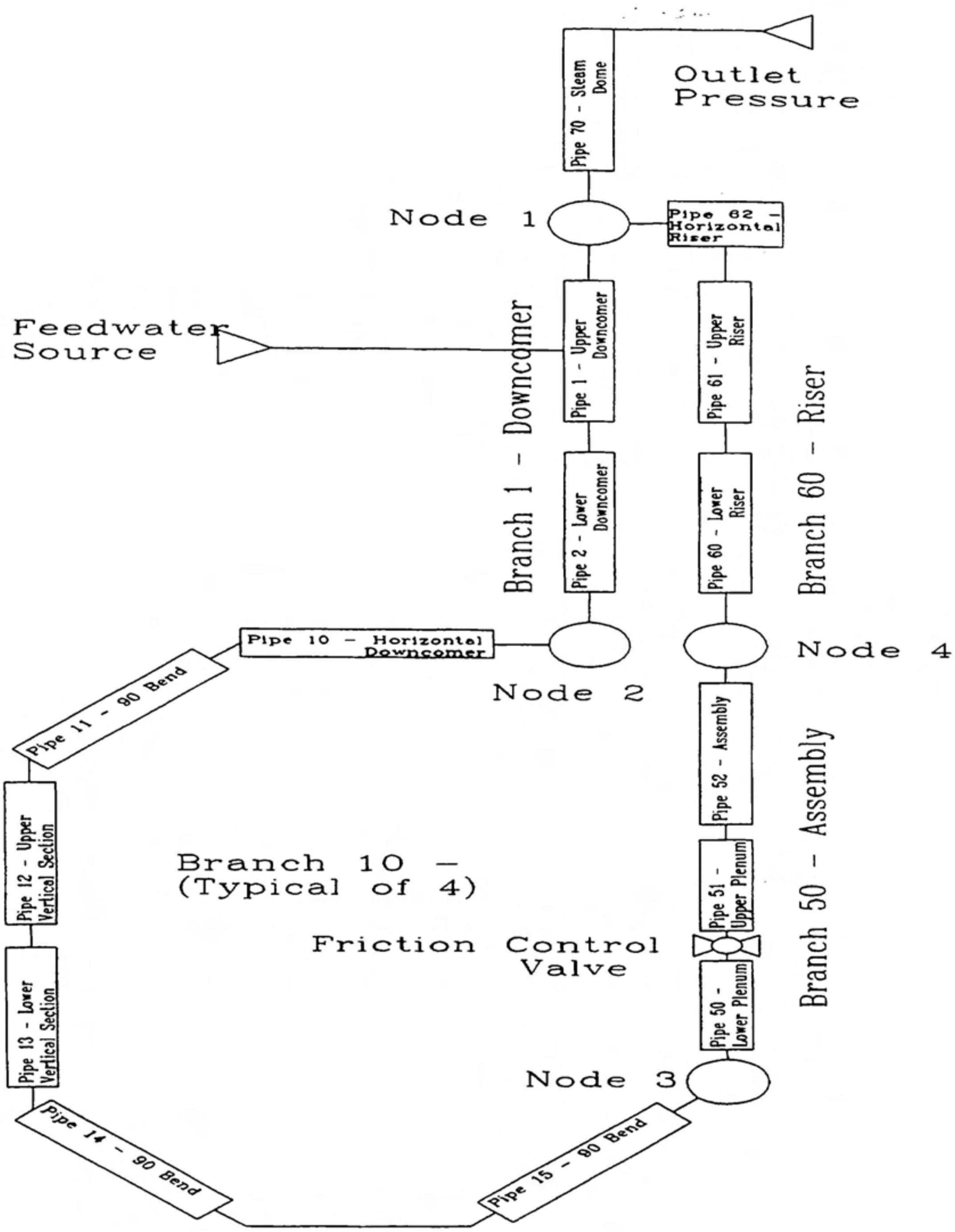
FIGURE 1 - DESIRE ASSEMBLY LAYOUT

monitored at various locations with five different absolute sensors, and the collapsed liquid level above the riser exit is measured with a differential pressure sensor. Vortex flow meters are provided in each of the four downcomer loops, and at the feedwater inlet and the steam dome exit. Finally, the axial void fraction distribution in the downcomer and the fuel assembly can be measured using gamma transmission tomography instrumentation designed by IRI.[6]

IV. MONA SCALING LAW VERIFICATION OF THE DESIRE FACILITY

A MONA model of the freon-cooled DESIRE facility was generated from the as-built dimensions.[5] Each independent flow path is defined as a "branch" within MONA. These branches can be composed of multiple "pipes", with each pipe consisting of "segments" of arbitrary length. The individual branches are connected at "nodes". The MONA model of DESIRE is shown in Figure 2. Referring to the figure, the upper and lower downcomers, the lower and upper inlet plenums, the heated assembly, the fixed and telescoping riser, and the steam dome are each composed of a single pipe with variable section lengths. Each of the four downcomer loops was modelled explicitly, with five separate pipes required to describe the geometry. Entrance loss coefficients were defined to account for transition effects in the

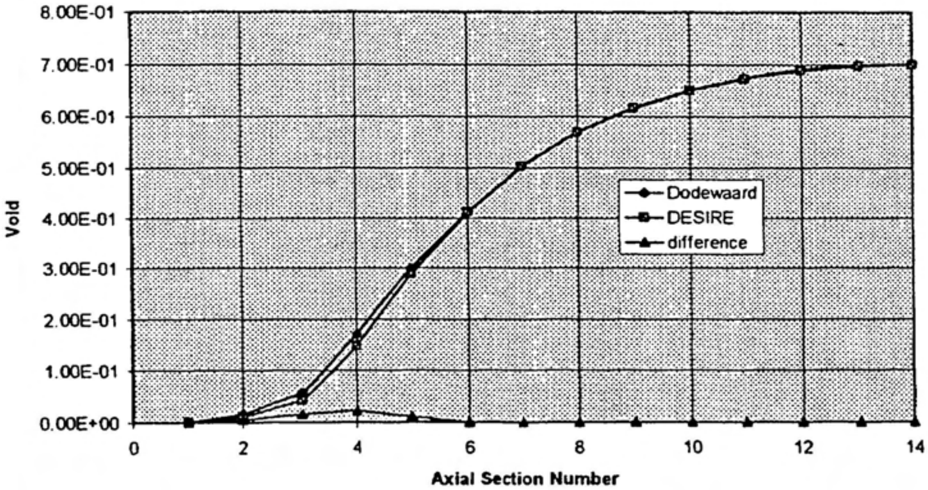
Figure 2 - MONA Model of DESIRE



system, the ninety-degree bends in the downcomer loop piping, and the assembly spacers. The friction control valve was included directly. A cosine-shaped axial power distribution was input for the heated rods. No radial power distribution can be applied in the current model. The feedwater inlet temperature and flow rate and the steam dome outlet pressure are specified as boundary conditions.

The IRI scaling law analysis was verified by also developing a MONA model of a fictitious full-scale, DESIRE facility that uses water, rather than freon-12, as the coolant. This was accomplished by dividing each of the component dimensions in the MONA model by the theoretical geometry scaling factor of 0.4612 that was previously specified in Table 1. The system pressure in this model was set at the nominal Dodewaard value of 75.5 bars, the power was increased by a factor of fifty, and the initial temperatures were adjusted to the level of 290 °C. The choice of freon-12 as a coolant automatically defines these system parameters of power, temperature, and pressure when scaling on all possible flow regimes is performed. Referring back to Table 1, this fact implies that only the inlet subcooling and mass flux can be adjusted using MONA inputs. These parameters are calculated values, however, and cannot be input directly. The feedwater inlet temperature and the position of the friction control valve were thus adjusted in the two models until the scaling ratios defined in Table 1 were obtained for these parameters. The resulting predicted axial void profiles for the Dodewaard and DESIRE flow assemblies are shown in Figure 3. The heated assembly was partitioned

Figure 3 - Assembly Axial Void Profile



into fourteen axial sections in the MONA models, so the axial sections displayed on the figure correspond to a length of 6.285 and 13.6 centimeters in the DESIRE and Dodewaard models, respectively. Comparing the two curves, excellent agreement is noted between the axial void profiles predicted for the water- and freon-cooled assemblies. The maximum error occurs in the vicinity of axial section four. MONA predicts that the flow regime in this location is bubbly and, as previously noted, no appropriate scaling criteria were derived for this flow regime due to the neglect of viscous effects and the lack of an appropriate "fluid-to-fluid" bubble development model. This result is also consistent with those of previous authors[3] who have performed scaling analysis for freon/water systems using a one-dimensional, two-fluid model - excellent agreement in the measured slip ratio was obtained in full-scale water and reduced freon systems when both the Weber and Froude numbers were matched, except for the bubbly flow region where viscous effects cannot be ignored. Since the scaling analysis that was used to design the DESIRE flow loop emphasized the local void fraction and flow pattern development, these results verify that the scaling analysis was performed correctly. The MONA calculations, which were performed with a realistic seven-conservation equation model, thus validate the theoretical scaling criteria that were developed using the simpler one-dimensional drift-flux model.

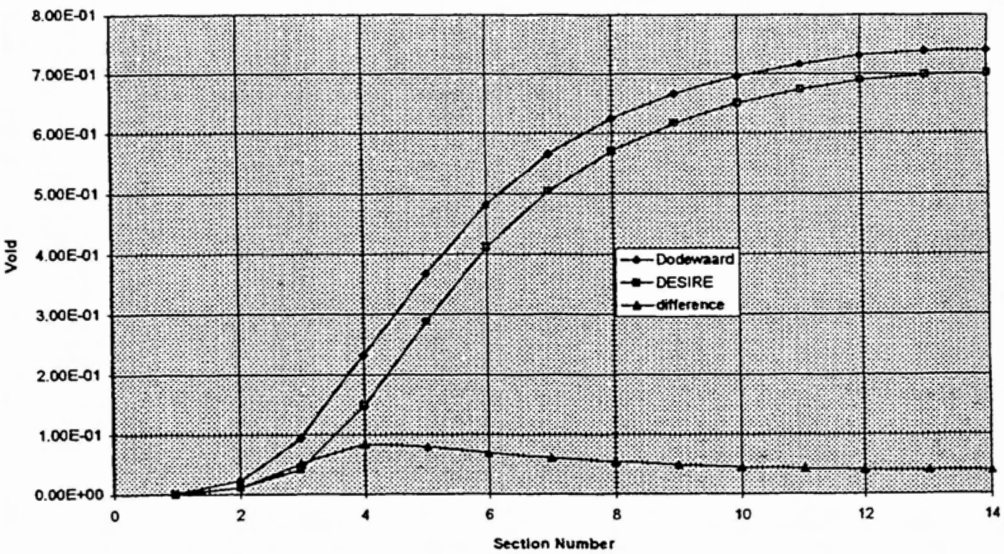
The previously described verification of the IRI scaling law analysis was performed by "back-scaling" the DESIRE facility to an equivalent full-size, water cooled system using the ideal value of 0.4612 for the geometry scaling parameter. This activity revealed that the pitch and the diameter of the fuel rods had not been scaled consistently, however. This results in the scaled DESIRE facility having the practical scaling that is illustrated in Table 2. The hydraulic

TABLE 2 - DESIRE Practical Scaling Parameters

Parameter	Dodewaard (water)	DESIRE (Freon-12)	Scaling
Rod Diameter (mm)	13.5	6.35	0.47
Pitch (mm)	17.9	8.8	0.49
Hydraulic Diameter (mm)	16.9	9.2	0.54
Flow Area (mm^2)	6981	1776	0.25

diameter and the flow area of the heated assembly are too large relative to the dimensions of the Dodewaard fuel assemblies. A third MONA model, corresponding to the real Dodewaard fuel assembly dimensions, was thus generated. Figure 4 illustrates a comparison between the predicted axial void fraction variation for a water-cooled flow facility with the fuel assembly dimensions used in the actual Dodewaard reactor and the actual DESIRE facility. Referring

Figure 4 - Assembly Axial Void Profile

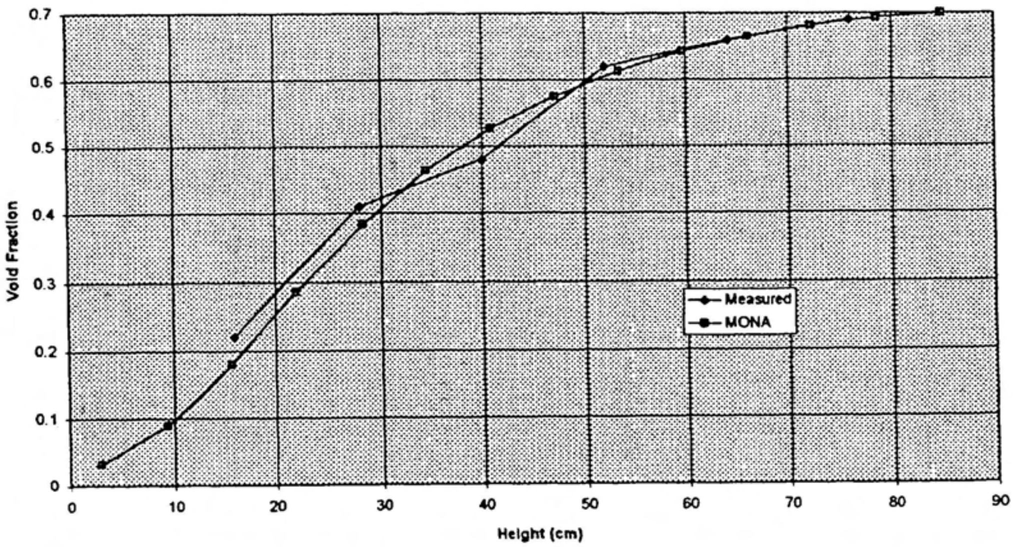


to the figure, it can be seen that the actual DESIRE facility under-estimates the void fraction, relative to the Dodewaard values, at each axial section due to the discrepancy in the rod pitch to diameter ratio. It would appear that this effect represents a constant bias after the fourth axial segment. Thus, it may be possible to correct the measured DESIRE void fractions to the corresponding Dodewaard data in the future using the MONA model. It is noted that this effect does not influence the dynamics of the natural circulation flow. The observed bias is only of interest when trying to directly compare the measured DESIRE and Dodewaard data.

V. BENCHMARKING OF THE MONA DESIRE MODEL

A preliminary calculation has been performed to benchmark the MONA model of DESIRE against the available experimental data. This case corresponds to the DESIRE measured operating conditions with the power set at 40 kW, the feedwater mass flow rate set at 0.244 kg/s, and the corresponding feedwater temperature at 5 °C. The recirculation flow rate was adjusted to 1.6 kg/s using the friction control valve, which results in the heated assembly inlet subcooling being established at 1 °C with the measured carry-under mass flow rate (i.e., the vapor that exits the riser and is dragged into the downcomer flow stream) at 0.057 kg/s. The power, and the feedwater mass flow rate and corresponding temperature were input to MONA directly. The friction control valve was adjusted to obtained the required flow rate within the MONA model, as is done in the actual DESIRE facility. The carry-under exhibits a significant influence on the natural circulation flow due to a reduction of the density of the liquid in the downcomer. This phenomenon also has an effect on the assembly inlet subcooling since some of the feedwater entering the downcomer must be used to condense the vapor. The carry-under is input as a volume fraction of the steam flow rate in MONA, so this input value was also adjusted to obtain the appropriate values. Adjustment of these inputs yielded a MONA predicted recirculation flow rate of 1.652 kg/s, with 1.04 °C subcooling and a carry-under mass flow rate of 0.052 kg/s. The measured and predicted axial void profiles are compared in Figure 5. Referring to the figure, the MONA predicted axial void profile exhibits

Figure 5 - Measured Versus Predicted
Axial Void Profiles @ 40 kW



excellent agreement with the experimental data for this case. The measured axial void profile was obtained using the IRI gamma transmission tomography instrumentation.[6] In this device a gamma radiation beam is passed through the flow subchannel and the attenuated beam is measured on the opposite side. This provides an indication of the void fraction present in the subchannel because the vapor is less effective than the liquid in attenuating the radiation beam.

The two-dimensional void fraction distribution within the subchannels is obtained at each axial location by performing these measurements at multiple points around the heated assembly and subsequently applying tomographic reconstruction techniques.[7] Five hundred such directions were used at each axial location shown in the previous figure, so the experimental uncertainty in the measured average void fraction is small. It is noted that the entrance loss coefficients that have been defined in the MONA were developed from simple empirical correlations. IRI will measure the pressure drop at these junctions in the future to determine the appropriate inputs for MONA, although the results that we have obtained to date are acceptable. IRI will perform additional calculations at other DESIRE operating conditions to complete the benchmarking of the MONA model as more experimental data become available.[8]

VI. CONCLUSIONS AND RECOMMENDATIONS

The drift flux model scaling law analysis that was performed by IRI to design the DESIRE facility has been verified using the two-fluid model contained in MONA. This study also revealed that a discrepancy exists between the ideal and actual DESIRE scaling criteria regarding the fuel rod pitch to diameter ratio. MONA predicts that a "constant bias" exists between the axial void profiles present in the Dodewaard fuel assemblies and the DESIRE heated assembly due to this difference. Future theoretical work will be performed to attempt and derive a theoretical basis for this biasing constant in the future. Additional benchmark comparisons between the MONA predictions and the DESIRE facility measured data will be performed as experimental data becomes available.

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