VALIDATION OF THE THIRST STEAM GENERATOR THERMALHYDRAULIC CODE AGAINST THE CLOTAIRE PHASE II EXPERIMENTAL DATA

J.M. Pietralik[(1)], A.O. Campagna[(1)], and V.C. Frisina[(2)]

ABSTRACT

Steam generator thermalhydraulic codes are used frequently to calculate both global and local parameters inside the steam generator. The former include heat transfer output, recirculation ratio, outlet temperatures, and pressure drops for operating and abnormal conditions. The latter are used in further analyses of flow-induced vibration, fretting wear, sludge deposition, and flow-accelerated corrosion. For these purposes, detailed, three-dimensional two-phase flow and heat transfer parameters are needed. To make the predictions more accurate and reliable, the codes need to be validated in geometries representative of real conditions. One such study is an international cooperative experimental program called CLOTAIRE based in France. COG participated in the first two phases of the program; the results of the validation of Phase I were presented at the 1994 Steam Generator and Heat Exchanger Conference, and the results of the validation of Phase II are the subject of this paper.

THIRST is a thermalhydraulic, finite-volume code to predict the flow and heat transfer in steam generators. The local results of CLOTAIRE Phase II have been used to validate the code. These consist of the measurements of void fraction and axial gas-phase velocity in the U-bend region. The measurements were done using bi-optical probes.

A comparison of global results indicates that the THIRST predictions, with the Chisholm void fraction model, are within 2 to 3% of the experimental results. Using THIRST with the homogeneous void fraction model, the global results were less accurate but still well predicted with the greatest error of 10% for the separator pressure drop.

Comparisons of the local predictions for void fraction and axial gas-phase show good agreement. The Chisholm void fraction model generally gives better agreement with the experimental data while the homogeneous model tends to overpredict the void fraction and underpredict the gas velocity.

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1. INTRODUCTION

Since the early 1970s, the deterioration of the reliability and performance of steam generators (SG) has led to shutdowns and significant unavailability of nuclear power plants. Costs attributed to steam-generator-related problems have been estimated to be in billions of dollars.

Some steam generators have experienced a wide array of corrosion, mechanical and flow-induced vibration problems. An advanced computer code solving 3-dimensional two-phase flow and heat transfer on the shell side can be used during the design, operation and problem-solving stages of a SG. In particular, predictions from such codes can be used to: carry out flow-induced vibration assessments; determine separator loading; investigate the flow, quality and heat flux distributions above the tubesheet to assess the propensity for sludge accumulation; calculate fretting-wear rate for dynamic interactions between tubes and tubes supports; and investigate the effects on flow distribution of modification to preheater compartments, tube-support configurations, flow distribution baffles, and downcomer window geometry.

A very important requirement of a computer code is its validation. For predictions to be reliable and accurate, computer codes should be validated against detailed measurements at a controlled environment in a geometry and operating conditions representative of those in SGs. One such study is an international cooperative experimental program called CLOTAIRE based in France. COG[1] participated in the first two phases of the program; the results of the validation of Phase I were presented at the 1994 Steam Generator and Heat Exchanger Conference, Ref. 1, and the results of the validation of Phase II are the subject of this paper.

2. THIRST CODE

THIRST[2] is a finite-volume, three-dimensional computer code that calculates detailed distributions of all necessary thermalhydraulic parameters in the shell side of SGs. It solves basic differential equations of continuity, momentum, and energy in control volumes.

The code assumes that the flow is steady and incompressible, the shell and shroud are adiabatic, the downcomer flow is two-dimensional (no change in the radial direction), laminar and turbulent stress forces are negligible in comparison with hydraulic resistances, and conductivity heat flux is negligible with the primary side heat flux. The tube supports and preheater baffles are treated as a hydraulic resistance in the axial direction only, and there is no carry-under (steam

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[1] COG: CANDU Owners Group

[2] THIRST: Thermal-Hydraulics In Recirculating STeam Generator

bubbles in the downcomer) nor carry-over (water droplets in the outlet steam). It was assumed that the tube bundle resistance is anisotropic since the resistance in the direction perpendicular to the tube is about 10-50 times larger than that in the direction parallel to the tube. This assumption is especially important in the U-bend region, where tubes are curved, thus affecting the hydraulic resistances.

Over the years the code has been improved in many ways. The improvements have been made to the pre- and post-processing capabilities, the computation scheme, the empirical correlations used, the modelling of internal structural elements, and the hydraulic model of the U-bend region and the preheater. In conjunction with these improvements, the code has been used to analyze the thermalhydraulic performance of SG designs for CANDU[3] and PWR[4] nuclear power plants.

THIRST has been verified by many analytical and experimental studies. That includes also a comparison of the results obtained from Phase I of the Clotaire program, Ref. 1. A further validation of detailed measurements of void fraction and gas axial velocity in the U-bend region is presented in this paper. The code version used for it is THIRST-V4R1.

3. CLOTAIRE PROGRAM

CLOTAIRE is an experimental program involving a large-scale model steam generator proposed by the French companies Framatome, Électricité de France (EDF), Commissariat à L'Énergie Atomique (CEA) and their sponsors. The program goals were to obtain detailed measurements suitable for the validation of computer codes used by these organizations for steam generator simulation, and to provide a forum for inter-code comparison and improvement of these codes. The experimental program was designed to simulate the thermalhydraulic and vibrational behaviour of a typical recirculating SG in a well-controlled laboratory environment.

For Phase-I of the experimental program, the external partners were National Power (formerly Central Electricity Governing Board) from the United Kingdom, Ansaldo from Italy, Mitsubishi Heavy Industries (MHI) from Japan, Electric Power Research and Westinghouse Electric Corporation (WEC) from the United States, and CANDU Owners Group (COG) from Canada. Participants in Phase-II of the experimental program were CEA, EDF, Framatome, MHI, COG and WEC.

The general objectives of the CLOTAIRE experiments are to:

i) generate global and local data for the validation of multi-dimensional thermalhydraulic computer codes,
ii) investigate the flow-induced vibration behaviour of U-tubes subjected to two-phase flow conditions, and
iii) provide insight into the detailed thermalhydraulic behaviour of steam generators.

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[3] CANDU: CANada Deuterium Uranium; registered trademark

[4] PWR: Pressurized Water Reactor

3.1 Clotaire Mock-up Description

The CLOTAIRE mock-up, Ref. 2, (Figure 1) consists of a lower portion containing a U-tube bundle enclosed in a half-cylindrical shell, and an upper portion equipped with three separators and a dryer assembly enclosed in a cylindrical shell. Recirculation is achieved by a hybrid downcomer made up of external pipes in the upper section and an annulus in the lower section. The mock-up, which can operate in natural or forced circulation mode, has a U-tube bundle with the following characteristics:

vertical geometric scale	= 0.7	shell diameter	= 0.74 m
bundle height	= 7.2 m	average tube length	= 14 m
number of U-tubes	= 184	U-bend anti-vibration bars	= "I" or "V"[5]
no integral preheater		number of support plates	= 9
distribution baffle	= 1	number of tube rows	= 15
tube O.D.	= 13.3 mm	tube I.D.	= 11.3 mm
tube pitch	= 19.64 mm	tube arrangement	= square pitch

Freon 114 at 0.9 MPa was used to simulate a secondary-side steam-water mixture at 7.0 MPa. Detailed experimental and analytical work was carried out with both fluids, to determine the ability of Freon 114 to adequately represent the behaviour of a high-pressure steam-water mixture. Pressurized water at 0.6 MPa was used on the primary side.

To improve flow stability in the U-bend region and repeatibility of the measurements near the top tube bundle boundary, a horizontal perforated plate was installed in the region above the tube bundle. The flow stabilizing device (FSD) resembles a normal support plate with 0.0152 m diameter holes at a pitch of 0.021 m arranged in a triangular pattern. In each test, the plate was located at such an elevation that the plate stabilized the flow above the tube bundle; for test TR-535, the elevation was 383 mm above the tube bundle. The flow stability was determined visually from ports located in that region.

3.2 Phase II Experiments

The main focus in Phase II experiments was on local measurements of void fraction and gas axial velocity in the U-bend region. The mock-up is instrumented with movable bi-optical probes at different levels to measure the void fraction and the axial gas-phase velocity (Figures 2 and 3). The measurements are taken horizontally with a step of ¼ tube pitch, i.e. five measurements per sub-channel. In the tube bundle, the five local data obtained within the same sub-channel are combined to determine a surface-average (surfacic) value for the sub-channel. The surfacic values should be used when comparing the data to the THIRST predictions since the surfacic values should be representative of the volume average velocity which the model calculates.

[5] "I" anti-vibration bars are 90 degrees from the horizontal plane and are at the vertical plane of symmetry and "V" anti-vibration bars are 60 degrees from the horizontal plane and are symmetric about the vertical plane of symmetry.

The functions used to convert the local measured values into the surfacic values were developed in a separate experiment for parallel and cross flows, Ref. 3. The electrically heated test section consisted of a 4x4 array of tubes arranged in a square-pitch configuration. For Phase II, different conversion correlations were used depending on measurement location. Conversion curves for void fraction and axial gas velocity were developed for the parallel-flow configuration and for cross-flow configurations fully within the tube bundle and at the bundle edge.

In Phase II several tests were performed with different power levels and for further analysis, a test at 100% nominal power, test TR-535, was selected. Important parameters for this run are presented in Table 1.

Table 1: CLOTAIRE Phase-II Test Operating Conditions, Ref. 2

Operating Conditions	**Unit**	**TR-535**
Power Level	% nominal	100.2
Movable Grid Position Distance Above Tube Bundle	m	0.383
Feed Flow	kg/s	15.04
Recirculation Ratio	-	3.35
Feed Temperature	°C	81
Feed Flow in Hot Leg	%	77.8
Recirculation in Hot Leg	%	50.1
Dome Pressure	MPa	0.888
Downcomer Liquid Level	m	10.43
Primary-Side Flow	kg/s	60.12
Primary-Side Pressure	MPa	1.01

4. RESULTS AND DISCUSSION

4.1 Global Results

The global results measured at 100% nominal power have been compared with THIRST predictions. Two void fraction correlations were used in THIRST modelling: the homogeneous model commonly used in vibration applications, and the Chisholm correlation, Ref. 4. A comparison of the global measurements and the predictions is shown in Table 2.

Table 2: THIRST Global Predictions and Relative Differences for Chisholm and Homogeneous Void Fraction Models

Test Run	Case	Units	Heat Transfer	Total Flow	Feed Flow[(1)]	Recirculation Ratio	Separator Pressure Drop
			MW	kg/s	kg/s	-	kPa
TR-535	CLOTAIRE Measurements	Physical	2.976[(2)]	130.86	15.04	3.350	19.50
	THIRST-Chisholm	Physical	3.001	128.87	15.10	3.268	20.13
		%[(3)]	0.8	-1.5	0.4	-2.4	3.2
	THIRST-Homogeneous	Physical	3.056	137.67	15.38	3.477	21.46
		%[(3)]	2.7	5.2	2.2	3.8	10.0

(1) For the mock-up geometry, which is equivalent to a half of a SG
(2) Taken as an arithmetic average of the primary and secondary side heat transfer rate
(3) The values are calculated as (Value Predicted - Value Measured) / Value Measured * 100%

As seen from the table, the agreement is very good, and the maximum relative difference is for the separator pressure drop. For that parameter, the Chisholm model results in 3.2% difference and the homogeneous model renders 10%. Comparing the two models, the Chisholm void fraction model gives more accurate results.

4.2 Local Results

For local results, a comparison was done for measurements in the U-bend region, where parameter variations are largest. Figure 4 shows the normalized axial gas velocity around four tubes at a distance 0.081 m from the back plate. These plots show the measured and predicted axial gas velocities vs. angular position measured clockwise from the cold side; therefore, the cold side extends from 0° to 90° and the hot side from 90° to 180°. The distance is chosen sufficiently far from the back plate to avoid its effects. The plots show conditions for radii equal to 69 mm, 207 mm, 288 mm, and 308 mm. The first two radii describe the tubes inside the bundle, the third corresponds to the largest tube at that distance, and the fourth radius is larger by one tube pitch than the largest tube at that distance. Figure 5 shows the void fraction comparison in the same arrangement as for axial gas velocity.

Both predicted parameters are in good agreement with measured ones. The axial gas velocity is better predicted in the cold side. The Chisholm correlation is marginally better than the homogeneous model, especially for the void fraction distributions.

Figures 6 and 7 show the predicted and measured values of axial gas velocity and void fraction, respectively vs. distance from the back plate. The plots are made for a U-bend radius of 288 mm at four angular positions: 37.5°, 78°, 102°, and 142.5° from the horizontal measured clockwise starting at the cold side. The distance shown in the plots extends beyond the tube bundle. The measurements up to a distance of 120 mm from the back plate are located inside or just above the tube bundle, and the rest is outside the bundle.

The plots show a good agreement for both the axial gas velocity and the void fraction outside the bundle. Some measurements in that region exhibit large point-to-point changes, see those closer to the shroud. Inside the bundle, the void fraction predictions are in satisfactory agreement with the measurements, with the Chisholm model predictions better than the those for the homogeneous model. The calculated axial gas velocity values agree quite well in the central part (Figures 6b and 6c), but are not as well in the region outside it (Figures 6a and 6d).

There are several sources of discrepancy between the predicted and measured values. On the prediction side, the contributing factors are:

i) the models for the support plates and antivibration bars (AVB) were too simplistic. The models assumed a uniform hydraulic resistance over the support plates and for the ABSs, thus underpredicting their effect on the flow in the central part.
ii) the accuracy of the experimental correlations for heat transfer and pressure drop used in THIRST, especially the correlations for two-phase pressure drop multiplier and void fraction.
iii) the interpretation and interpolation method used to determine local predictions may introduce a significant error in regions with large changes over a short distance (across the bundle),
iv) the symmetry boundary condition applied at the central plane simulates well a real SG, but is not realistic for the mock-up, and
v) the assumptions, grid and solution approximations of the algorithm.

On the experimental side, there are several factors affecting the measurement accuracy:

i) the orientation of the bi-optical probe may not have been well aligned with the local velocity vector. A single orientation was used in each position. This orientation was determined by rotating the bi-optical probe at a location 0.0414 m from the back plate until the maximum reading was obtained.
ii) the empirically-derived conversion functions used to obtain surface-average value from local values were determined for parallel flow and separately for 90° cross flow. When applied in the U-bend region, where the flow is at varying angles to the tubes, it is expected to have a larger error.
iii) the measurements were difficult to obtain due to local flow fluctuations. In some locations there was no cross correlation between the two probes; thus no axial gas velocity could have been determined,
iv) inaccuracies of the probes, and
v) measurements in two-phase flows are always less accurate.

5. CONCLUDING REMARKS

In this validation study, the THIRST-V4R1 code was used to model the steady-state thermalhydraulic conditions in the CLOTAIRE Phase-II experiment. Phase II concentrated on local measurements of void fraction and axial gas velocity in the U-bend region. THIRST global predictions and local results in the U-bend region were compared with the experimental data.

The purpose of this paper was to evaluate THIRST against the most comprehensive set of large-scale steam generator data available.

The global comparisons found in Table 2 indicate that the THIRST predictions, with the Chisholm void fraction model, are within 2 to 3% of the experimental results. Using THIRST with the homogeneous void fraction model, the global results were less accurate but still well predicted with the greatest error being for the separator pressure drop.

Comparisons of the local predictions for void fraction and axial gas-phase show good agreement. The Chisholm void fraction model generally gives better agreement with the experimental data while the homogeneous model tends to overpredict the void fraction and underpredict the gas velocity.

6. ACKNOWLEDGEMENTS:

The authors gratefully acknowledge the financial support of CANDU Owners Group, Technical Committee No. 19, Steam Generators.

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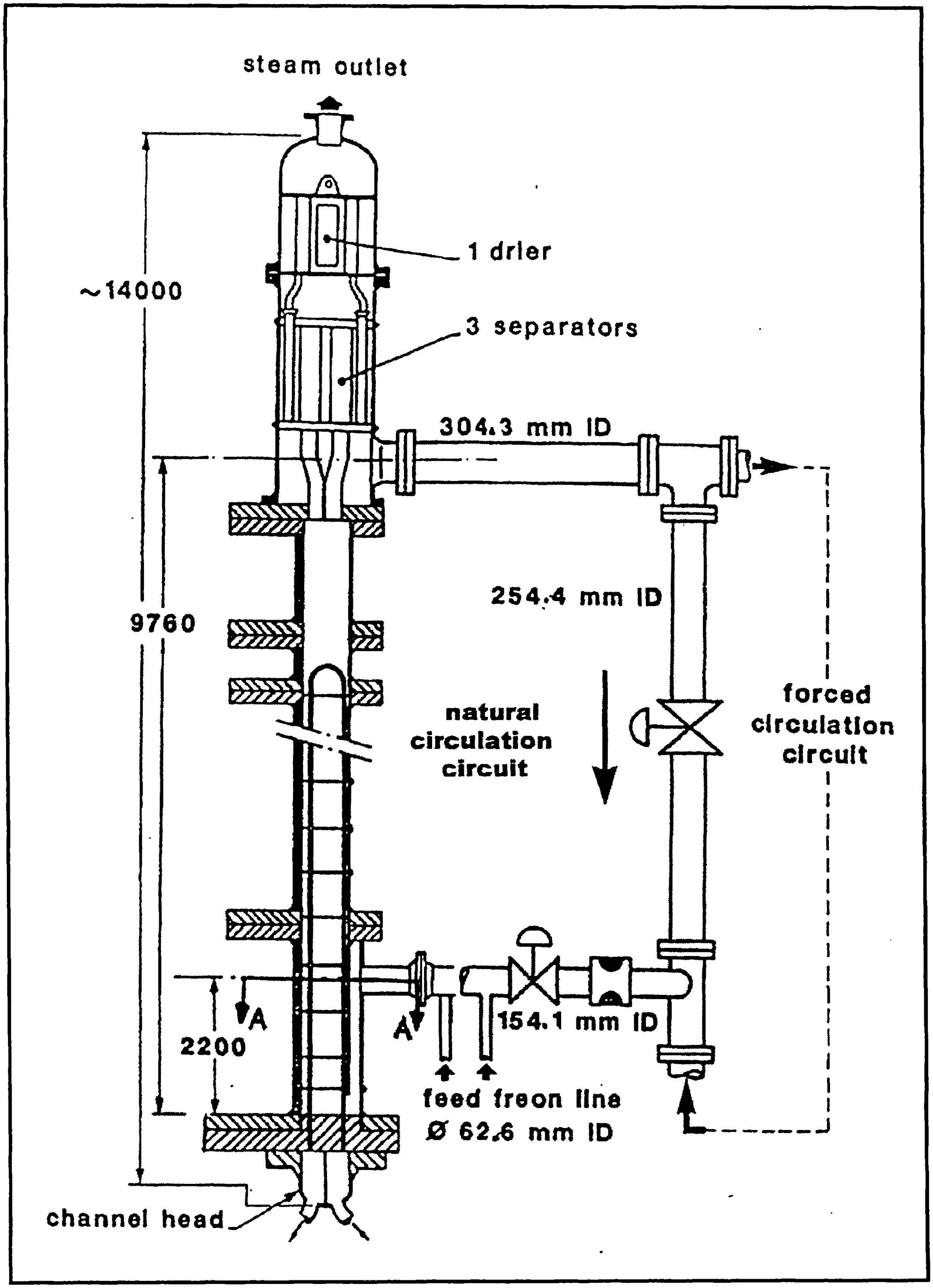


Figure 1: CLOTAIRE Mock-up, Vertical Cross-Sectional View.

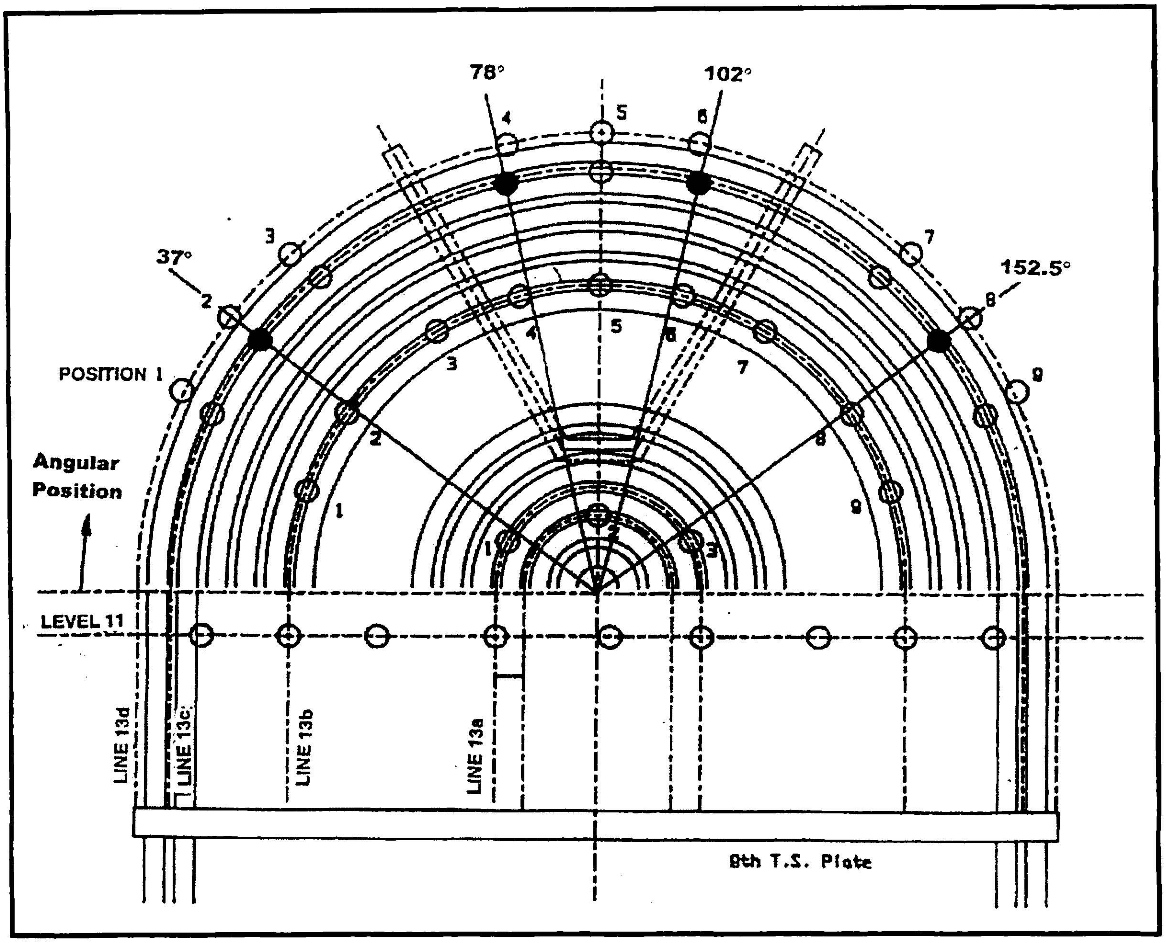


Figure 2: CLOTAIRE Phase-II Bi-Optical Probe Locations in the U-Bend Region, Front View. The black circles show the locations where the plots of local parameters vs. distance from the back plate are made.

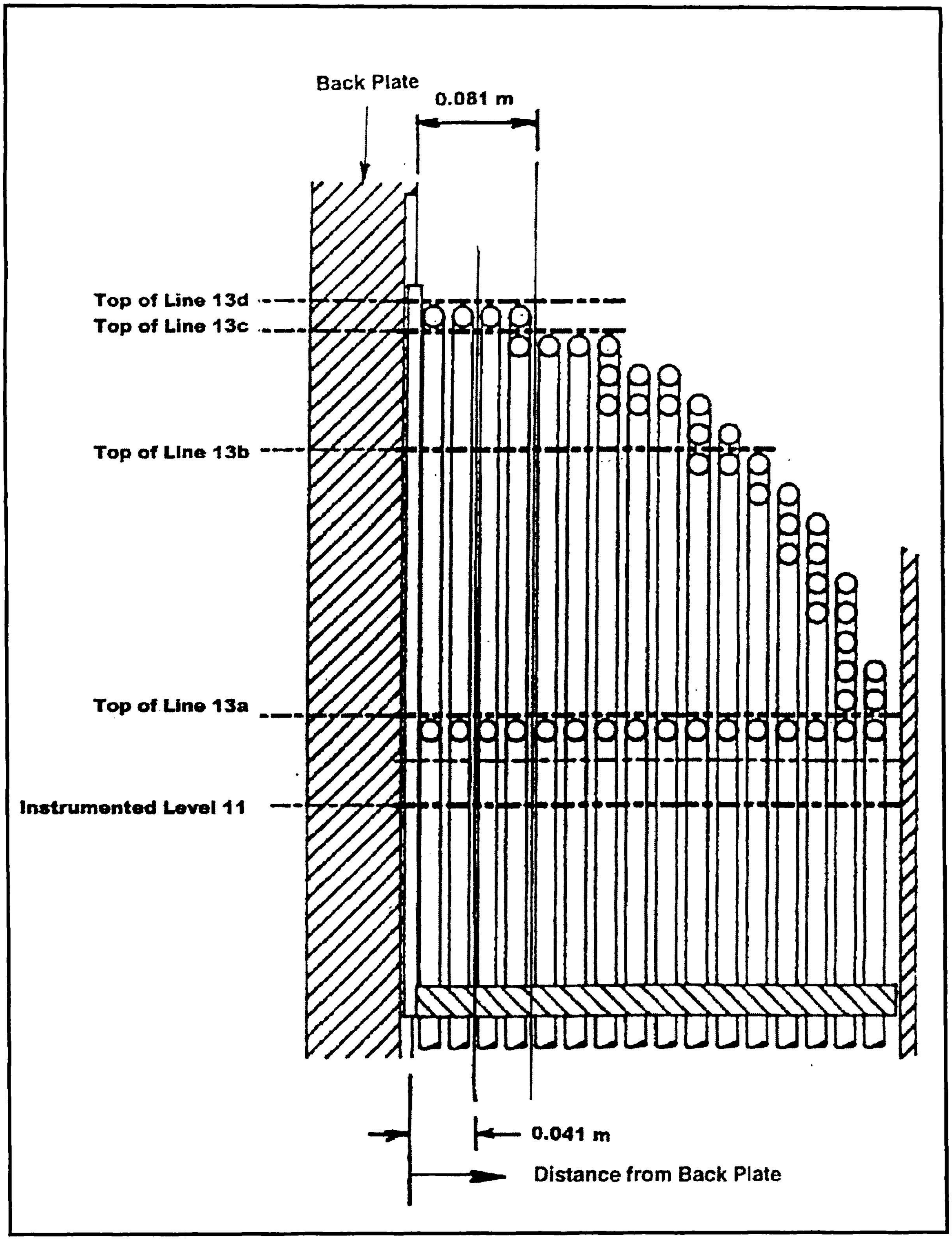
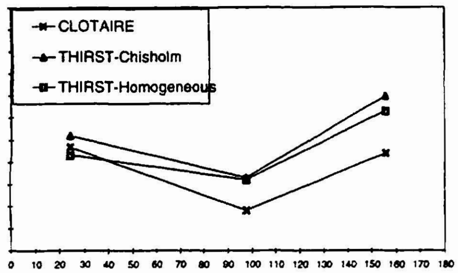
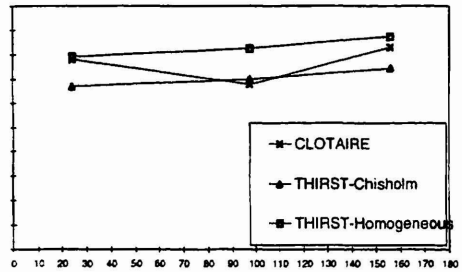
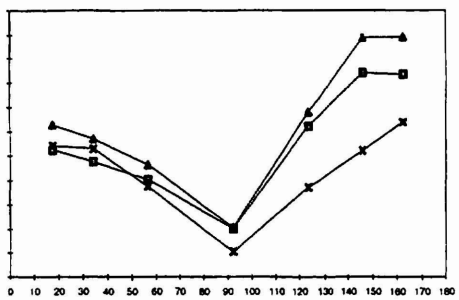


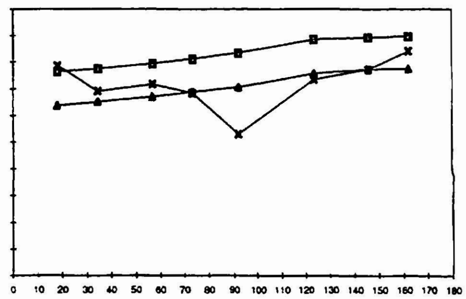
Figure 3: CLOTAIRE Phase-II Bi-Optical Probe Measurements vs. Distance from the Back Plate in the U-Bend Region, Side View.



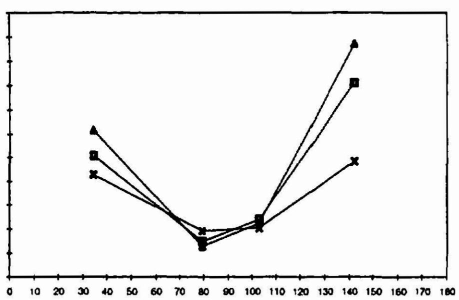


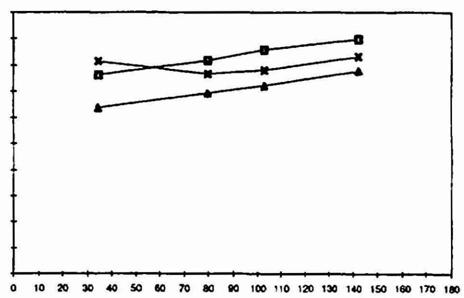
a) U-bend Radius 0.069 m (Line 13a)



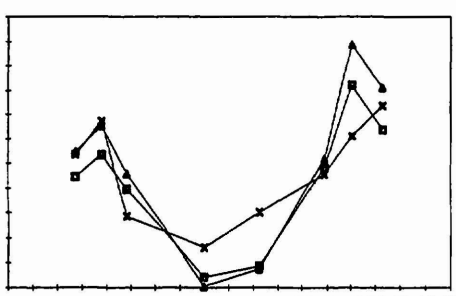


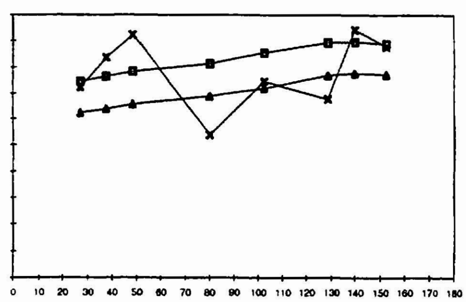
b) U-bend Radius 0.207 m (Line 13b)





c) U-bend Radius 0.288 m (Line 13c)

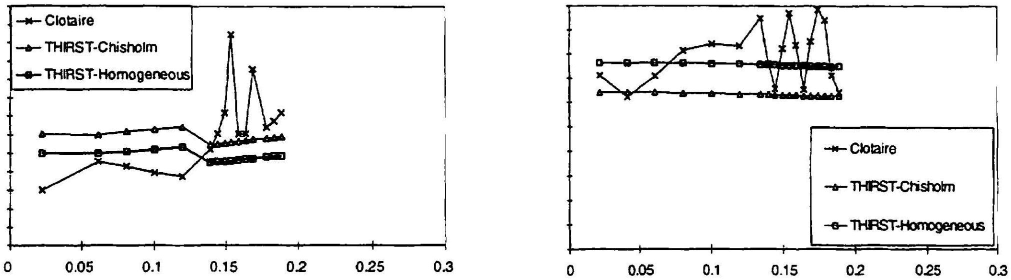




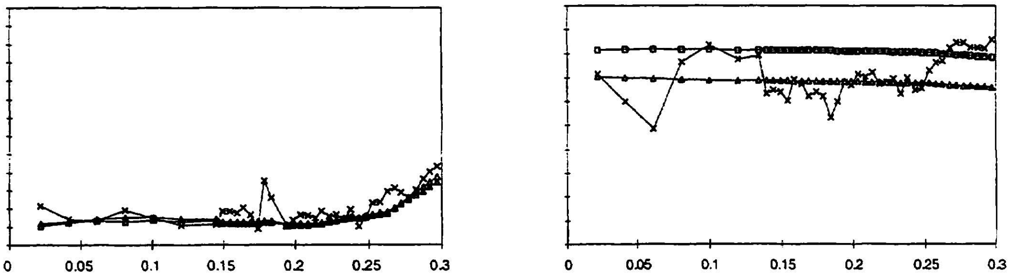
d) U-bend Radius 0.308 m (Line 13d)

Figure 4: Normalized Axial Gas Velocity vs. U-bend Radius for a Distance from the back plate of 0.081 m. Angular Position is from the Horizontal Measured Clockwise from the Cold Side.

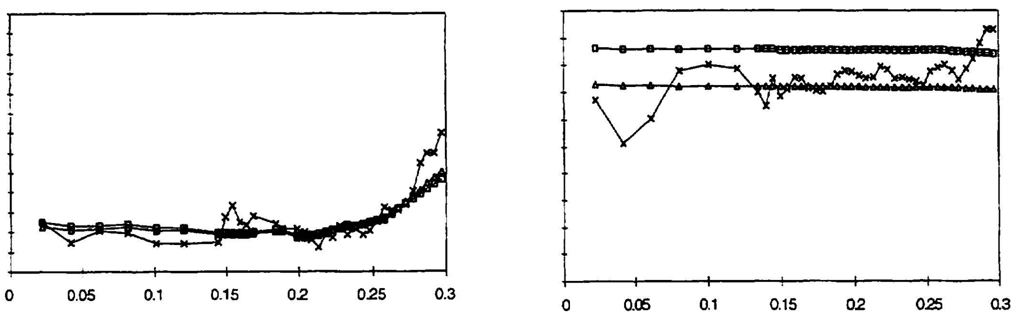
Figure 5: Normalized Void Fraction vs. U-bend Radius for a Distance from the back Plate of 0.081 m. Angular Position is from the Horizontal Measured Clockwise from the Cold Side.



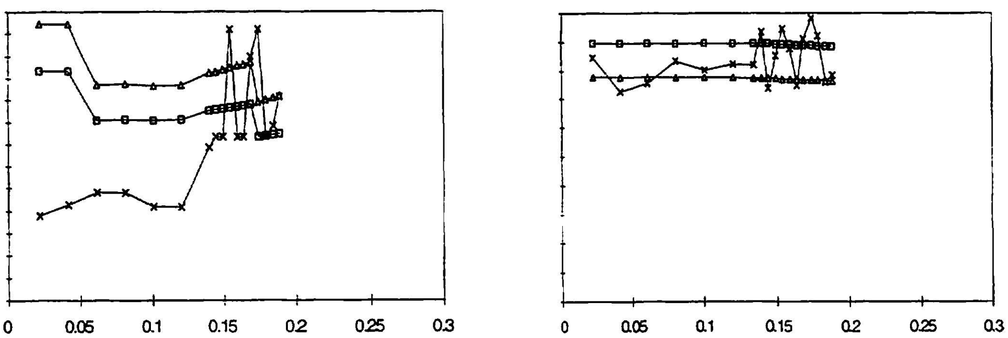
a) Angular Position = 37.5 degree



b) Angular Position = 78 degree



c) Angular Position = 102 degree



d) Angular Position = 152.5 degree

Figure 6: Normalized Axial Gas Velocity vs. Distance from the Back Plate (m) for a U-bend radius 0.288 m. Angular Position is from the Horizontal Measured Clockwise from the Cold Side.

Figure 7: Normalized Void Fraction vs. Distance from the Back Plate (m), for a U-bend Radius 0.288 m. Angular Position is from the Horizontal Measured Clockwise from the Cold Side.

DISCUSSION

Authors: J.M. Pietralik, A.O. Campagna, V.C. Frisina, AECL

Paper: Validation of the THIRST Steam Generator Thermalhydraulic Code Against the Clotaire Phase II Experimental Data

Questioner: J. Nickerson, AECL

Question/Comment:

Regarding unstable flow above the tube bundle, this was a problem with Clotaire Phase 1 results but I thought these were resolved for Phase 2 - is this the case or were Phase 2 experimental results still subject to this behaviour?

Response:

Flow in the space between the tube bundle and the separator deck in Phase I experiments was unstable to the extent that the measurements in the U-bend region were not reliable. There was little cross-correlation of the signals from the two probes. Visual observations through a port confirmed that there were large-scale, low-frequency fluctuations of the two-phase flow in the region.

In Phase II experiments, the flow in this region was made less unstable by adding a perforated, horizontal plate above the tube bundle. This resulted in better measurements, although at some locations there were still fluctuations producing little cross-correlation. The number of such measurements, however, was small, a few percent of the total number of measurements. It is expected that the flow instability increases the measurement error in this region, although it is difficult to quantify it.