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TWO-DIMENSIONAL COMPUTATIONAL MODELING OF SODIUM BOILING IN SIMULATED LMFBR FUEL-PIN BUNDLES*

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Summary

Extensive sodium boiling tests have been carried out in two simulated LMFBR fuel pin bundles in the Thermal-Hydraulic Out-of-Reactor Safety (THORS) Facility at Oak Ridge National Laboratory. Experimental results from a 19-pin bundle (THORS Bundle 6A) have been previously reported,[1,2] and experimental results from a 61-pin bundle[3] (THORS Bundle 9) will be reported soon. The results discussed here are from the 19-pin bundle. Preliminary analysis has shown that the computational methods used and conclusions reached are equally valid for the 61-pin bundle, as well as the 19-pin in-reactor Sodium Loop Safety Facility (SLSF) W-1 experiment.[4,5]

The main result of THORS sodium boiling experimentation is that boiling behavior is determined by two-dimensional effects, i.e., the rates of mass, momentum and energy transfer in the direction perpendicular to the axes of the fuel pins. Two-dimensional effects largely determine the characteristics of both static and dynamic instability. Meaningful data analysis and future test planning required that some form of *practical* two-dimensional computational model be developed.

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This model, THORAX, solves a two-dimensional transient pressure-drop (test section inlet-test section outlet) thermal-hydraulic boundary value problem. The solution algorithm is based on the iterative SIMPLE algorithm of Spalding and Patankar[6] applied to the conservation equations written in fully-implicit, transient, finite-difference form. It was found that accurate solutions are possible using only two flow channels — one representing the interior subchannels, the other the exterior (adjacent to the duct wall) subchannels. Two distinct modeling options will be discussed.

The first option is termed the porous blockage option for reasons which will become clear. Except for the following assumptions, the two-phase mixture is treated *as a liquid.*

1. A two-phase liquid fraction is calculated on the basis of local saturation temperature and enthalpy, assuming homogeneous no-slip flow.

2. This local liquid fraction is used to calculate a homogeneous friction factor[7] using an effective (McAdams)[8] two-phase viscosity. This friction factor is applied to the wall resistance term in the axial momentum equation.

3. The local liquid fraction is also applied to the body force term in the axial momentum equation and the transverse thermal conduction term in the energy equation.

These assumptions produce a region of increased axial resistance which is maximum at the center of the bundle, causing a substantial fraction of the axial flow to be diverted to the outer regions. This transverse flow is responsible for transporting a large amount of energy out of the boiling region. This model has produced remarkably accurate simulation of the two-dimensional growth rate of the boiling region and the resulting static (Ledinegg) excursion of the average flow to dryout for a wide variety of tests (natural and forced convection, 4 to 16 kW/pin) in THORS bundles, and for test 7B of the SLSF W-1[5] series (36 kW/pin). The assumptions can be easily programmed into any subchannel analysis code which solves a transient pressure drop boundary value problem (such as SABRE-2[9] or COBRA-WC[10]). The numerical solution of this problem is *much* easier than the full two-phase model (because the liquid-to-vapor density ratio is $\sim$1600).

A full two-phase solution option (homogeneous compressible equilibrium) was also developed to increase understanding of why the blockage model gives such consistently accurate results. A two-fluid model (with its attendant unknowns of non-equilibrium interphase heat and mementum transfer) would be necessary to describe the boiling dynamics completely, but the homogeneous equilibrium model appears to have the potential of providing a reasonable approximation. Most of the heat provided by the fuel pin simulators in this model is removed from the boiling region by axial and (more importantly) transverse convection, the magnitude of which the porous blockage model adequately simulates.

The test section inlet flow of Bundle 6A Test 73E Run 102A (15.8 kW/pin) is shown in Figure 1. The flow ramp to a level which results in boiling begins at zero seconds, boiling initiation occurs in the center of the bundle near the end of the heated section at approximately seven seconds, and the entire bundle cross-section is boiling at approximately sixteen seconds, resulting in a rapid flow excursion to a level which produces film dryout at approximately twenty-one seconds. THORAX calculations are ended when the maximum quality exceeds unity (the dryout criterion).

Two-dimensional effects are so important to sodium boiling in 19 and 61-pin bundles that even a relatively simple two-dimensional model — the blockage model — can accurately simulate the transient growth of the boiling region and the resulting flow excursion to dryout. While these effects will certainly be reduced in a full-size fuel assembly, there is little doubt that they will still be significant, especially in a parfait core.

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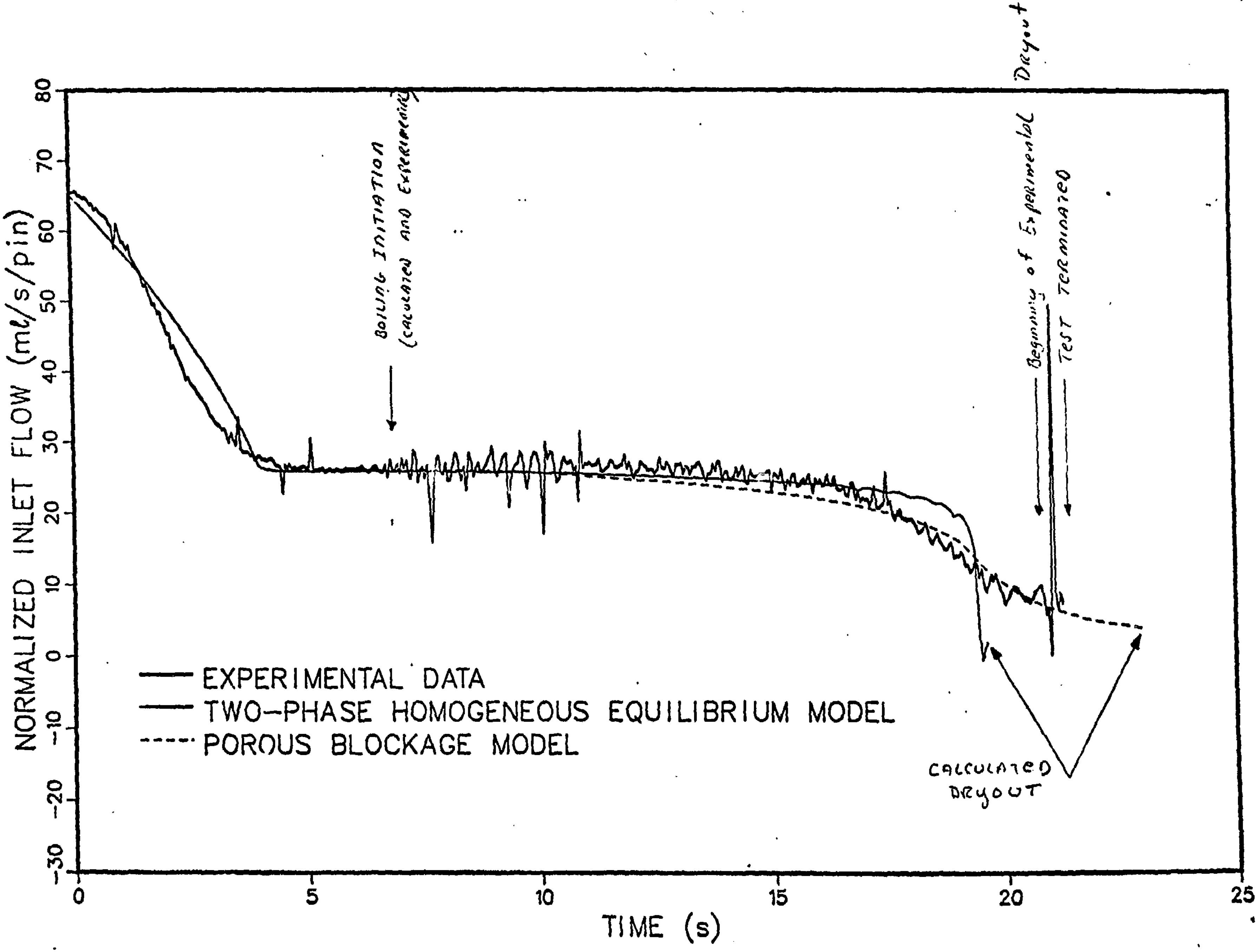
FIGURE CAPTION

Figure 1. Test section inlet flow for Test 73E, Run 102A, THORS Bundle 6A, and THORAX results for blockage and full two-phase models.



NORMALIZED INLET FLOW (mℓ/s/pin)
TIME (s)
80
70
60
50
40
30
20
10
0
−10
−20
−30
0
5
10
15
20
25
BOILING INITIATION (CALCULATED AND EXPERIMENTAL)
Beginning of Experimental Dryout
TEST TERMINATED
CALCULATED DRYOUT
EXPERIMENTAL DATA
TWO–PHASE HOMOGENEOUS EQUILIBRIUM MODEL
POROUS BLOCKAGE MODEL