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MASTER

Simulation of Low-Power,
Low-Flow Sodium Boiling with
a Transparent, Atmospheric
Pressure Water Loop

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**SIMULATION OF LOW-POWER, LOW-FLOW SODIUM BOILING WITH A
TRANSPARENT, ATMOSPHERIC PRESSURE WATER LOOP**

A. E. Levin J. J. Carbajo
B. H. Montgomery J. L. Wantland

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NOMENCLATURE

A	area
C	constant (Eq. 7.17)
C_p	specific heat at constant pressure
D	diameter
e	specific internal energy
f	friction factor
g	gravity
h	specific enthalpy
h	heat transfer coefficient (Appendixes B, C)
h_{fg}	latent heat of vaporization
I	inertance ($\rho L/A$)
k	thermal conductivity
K	loss coefficient
l, L	length
$\dot{m}$	mass flow
P	pressure
q	power
Q	volumetric flow
r	radius, radial variable
Re	Reynolds number ($\rho W D / \mu$)
S	slip ratio (W_g / W_f)
S/V_s	volumetric heat source
t	time
T	temperature
v	specific volume
v	axial velocity (Appendix A)
V	volume
w	axial velocity
x	quality
y	radial variable
z	axial variable

Greek

α	void fraction
ϵ	emissivity
μ	viscosity
ν	frequency
ρ	density
σ	Stefan-Boltzmann constant
τ	shear stress

Subscripts

c,com	compressible volume
conv	convection
f	liquid
F	friction
g	vapor
gl	glycerine
in	inside surface
K	valve losses
liq	liquid
m	mixture
o	reference
out	outside surface
rad	radiation
sat	saturation
T	total
vap	vapor space
w	water

Superscripts

j	axial node
*	dimensionless quantity

SIMULATION OF LOW-POWER, LOW-FLOW SODIUM BOILING WITH A
TRANSPARENT, ATMOSPHERIC PRESSURE WATER LOOP

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ABSTRACT

Experiments have been performed in a transparent, single-tube boiling loop, using water as the working fluid, to simulate sodium boiling behavior in a similar geometry. Testing has been performed over a wide range of flows, powers, and temperatures to examine the onset of boiling, flow regimes, oscillatory flow behavior, and dryout. Analysis of experimental data has been aided by the use of high-speed motion pictures. Instrument data from selected tests are presented and discussed, as well as results from computer simulations of the experiments. The computer model is presented, and scaling laws for the comparison of water and sodium oscillatory boiling are discussed. Comparison of the data from this loop with sodium boiling data has shown that an atmospheric pressure, two-phase water system is a good simulant for boiling liquid sodium.

1. INTRODUCTION

The liquid sodium coolant in a Liquid-Metal Fast Breeder Reactor (LMFBR) remains several hundred degrees Celsius below its saturation temperature during normal operating conditions. However, there exist hypothetical accident sequences in which the power and flow remain mismatched for a sufficient time to cause sodium boiling. Therefore, the study of sodium boiling behavior is an integral part of breeder reactor safety studies.

The Thermal-Hydraulic Out-of-Reactor Safety (THORS) Program at the Oak Ridge National Laboratory (ORNL) is part of the U.S. Department of Energy (DOE) Breeder Reactor Safety Program. As part of the THORS Program, sodium boiling studies have been performed using two experimental loops: the THORS facility¹ is a large, engineering-scale sodium loop for testing simulated LMFBR fuel bundles; the Sodium Boiling Test (SBT)

facility² is a single-tube natural circulation loop for the study of low-power sodium boiling. Tests in both the THORS and SBT loops have shown that sodium boiling is a dynamically unstable phenomenon, characterized by both high- and low-frequency oscillations in flow. Because of the opacity, high operating temperatures, and chemical reactivity of sodium, its boiling behavior must be inferred from pressure, temperature, void, and flow instrumentation; direct observation is not practical. This limitation has encouraged efforts to simulate sodium boiling with a non-metallic liquid with a low boiling temperature whose other physical properties would permit its two-phase behavior to resemble that of liquid sodium.

Previous work in sodium boiling simulation has been carried out at Argonne National Laboratory (ANL) and the Massachusetts Institute of Technology (MIT). Ford,³ at ANL, used Freon-113 as a sodium simulant in flow expulsion experiments using a simple, transparent, single-tube apparatus. Many of his experiments were run at pressures below atmospheric, and all of his experimentation consisted of short-duration tests so that continuous operation of the loop was not a major consideration.

Hinkle,⁴ at MIT, built a natural circulation loop using water as the simulant fluid. His choice of water was based primarily on ease of operation and the fact that the liquid-to-vapor density ratio of sodium at reactor conditions was well approximated by that of water at atmospheric pressure. Hinkle's test section consisted of a stainless steel tube with an inner diameter of ~3.9 mm, which is representative of the hydraulic diameter of a subchannel in an LMFBR driver assembly. The test section consisted of a short unheated length, simulating a lower axial blanket in an LMFBR fuel assembly, followed by a 914-mm-long heated section, representing the fueled zone of the assembly. Above this was an upper unheated section ~1220 mm in length, representing the upper axial blanket and fission gas plenum in a fuel bundle. It was directly heated by passing direct current through part of the test section wall and was instrumented with thermocouples and pressure transducers. There was no flow instrumentation, and flow visualization was accomplished by means of sight glasses installed at the test section inlet and outlet. Data

acquisition was done on a chart recorder and was too slow to allow anything other than steady-state natural circulation tests to be run. Hinkle's water loop design formed the basis for the design of the SBT facility at ORNL.

Finally, Levin⁵ built another water loop at MIT. Based on Hinkle's design, this loop used the same basic configuration as the previous apparatus. However, the two unheated zones were constructed of Pyrex glass to allow more extensive flow visualization. In addition, flow measurements were made using the differential pressure across an orifice, and thermocouples were inserted through the glass sections into the fluid, rather than being fastened onto the outside of the tube wall. A pump was also added to the system along with a bypass leg to allow more flexibility in testing. A fast-scan data acquisition system (DAS) was used in these experiments to enable transients to be run. Testing in this loop was oriented toward simulating sodium boiling tests in the THORS facility. While experimentation in this system was fairly successful, problems developed in flow measurement because of large pressure oscillations that accompanied boiling flow oscillations. These pressure pulses distorted the orifice differential pressures, thereby causing significant errors in measured flows. In addition, the flow behavior in the heated zone, which was still made of stainless steel, could not be observed directly.

Because of these shortcomings in previous experiments, the Simulant Boiling Flow Visualization (SBFV) loop was constructed at ORNL. The design of this single-tube water loop was based on the two previous MIT water loops, but several changes were made to correct previous problems.

This report describes the design and operation of the SBFV, as well as experimental results and analysis of data from the loop. Sections 2 and 3 contain a description of the experimental apparatus and instrumentation. Sections 4 and 5 discuss experimental procedures and results and present an analysis of selected tests. Section 6 is devoted to a comparison of SBFV data with sodium boiling data, while Sect. 7 discusses analytical modeling of the loop and several computer simulations of SBFV experiments. Section 8 contains the conclusions and future plans for SBFV experimentation. Several appendixes are also included, covering detailed aspects of the subjects in Sects. 2-8.

2. LOOP DESCRIPTION

Figure 2.1 shows the SBFV loop as originally designed and built. The test section is constructed entirely of Pyrex glass with an inner diameter of 4 mm and a 1-mm-thick wall. This design allows visual observation of all regions of the test section. Power is supplied to the water in the heated region by counterflow circulation of hot glycerine in an annulus surrounding the water tube. The inner diameter of the annulus is the same as the outer diameter of the test section tube, 6 mm. The outer diameter of the annulus (inner diameter of the large tube) is 13 mm. The outer tube wall is also 1 mm in thickness. Glycerine was chosen as the heating fluid because (1) its viscosity drops steeply as a function of temperature, (2) its boiling temperature is $\sim 290^{\circ}\text{C}$, and (3) its index of refraction is very close to that of Pyrex, allowing visual observation with minimal distortion. As an illustration of the strong temperature dependence of the viscosity of glycerine, at 20°C its value is 1.48 Ns/m^2 , whereas at 200°C it has dropped to $2.2 \times 10^{-4} \text{ Ns/m}^2$. This can be compared to the viscosity of water, which at 20°C is $\sim 1.03 \times 10^{-2} \text{ Ns/m}^2$. An additional benefit of glycerine is that it is a nonhazardous material. The length of the heated zone is $\sim 956 \text{ mm}$, about the same as the SBT loop. The upstream unheated length is $\sim 406 \text{ mm}$, and the outlet unheated zone is $\sim 1575 \text{ mm}$ long. The lengths are somewhat longer than the other water loops or the sodium loop; the extra space was required to allow installation of the flowmeters, which will be described in the following section.

The remainder of the loop is constructed of stainless steel. The upper and lower plenum tanks are similar in design to the SBT loop. They are both $\sim 197 \text{ mm}$ in diameter. The lower plenum is 203 mm long, and the upper plenum is 254 mm long. The upper plenum remains open to the atmosphere to maintain a constant pressure boundary condition. Both plena contain copper cooling coils through which water may be passed to maintain a constant temperature. Both the bypass and pump lines are 13-mm-diam stainless steel tubing. The glycerine system is also stainless steel. The tank is 197 mm in diameter and 203 mm long, and all of the glycerine lines are 19-mm-diam tubing, with the exception of the lines

Fig. 2.1. SBFV loop design and instrumentation.

connecting the glycerine system to the test section (at FE-30 and TE-26) (Fig. 2.1), which are 13 mm in diameter. Connection between the steel and glass tubing is accomplished using heat-shrinkable tubing on the glycerine system and Teflon tubing between the test section and the upper and lower plena.

The glycerine is heated by Calrod heaters inside the tank, controlled by two Variacs. The water and glycerine pumps are impeller driven and are rated at 1725 rpm at 90 V dc. The speed of each pump is controlled by varying the supply voltage so that the glycerine and water flows may be changed as required. The power delivered to the test section is calculated by a heat balance on the glycerine using the glycerine flowmeters and resistance temperature devices (RTDs) at the test section inlet and outlet.

The loop was operated in the configuration shown in Fig. 2.1 for a number of tests in two glass test sections. The second test section was "frosted" by roughening the inner surface of the water tube from the top of the heated section downward for ~450 mm. This provided easy visual confirmation of dryout, since the tube becomes semi-opaque as the water film evaporates. After the initial series of experiments, the loop configuration was altered to conform more closely to that of the SBT facility.

The SBT loop is shown in Fig. 2.2. When the loop was designed, the test section was patterned after Hinkle's water loop. However, since SBT operating temperatures were expected to range from ~300°C to 1000°C, a large coil was included at the test section inlet to accommodate the thermal expansion of the test section. This coil also served to provide an inlet resistance similar to that found in the inlet module of an LMFBR. However, the coil, which was ~2660 mm long, introduced an extremely large and nonprototypical inlet inertance (defined as the product of the liquid density and the test section length-to-cross-sectional area ratio, $\rho L/A$) into the system. This, in turn, affected the oscillatory behavior of the system (see Appendix A). Therefore, a coil design similar to that of the SBT loop was installed upstream of flowmeter FE-1 (see Fig. 2.1). This change allowed the determination of the effect of inlet inertance on system oscillatory behavior, as well as providing a

Fig. 2.2. Sodium Boiling Test Facility — test section.

closer simulation of SBT geometry. Table 2.1 lists some important geometrical parameters for both configurations of the SBFV loop as compared to the SBT loop.

A second series of experiments was successfully completed in the modified SBFV loop. Samples of data from both loop configurations and comparison of these data with SBT results are presented in Sect. 6.

Table 2.1. Comparison between SBT and SBFV designs

	SBT ^a	SBFV without coil	SBFV with coil
Tube diameter, D (mm)	3.25	4	4 ^b
Flow area, A (mm ²)	8.3	12.6	12.6
Inlet section			
Length, L (m)	2.84	0.442	~2.7
L/D	1078 ^c	110.5	~1100 ^c
L/A (m ⁻¹)	3.42 × 10 ⁵	0.35 × 10 ⁵	~3.4 × 10 ⁵
Heated section			
Length, L (m)	0.965	0.965	0.965
L/D	297	241	241
L/A (m ⁻¹)	1.16 × 10 ⁵	0.77 × 10 ⁵	0.77 × 10 ⁵
Outlet section			
Length, L (m)	1.506	1.610	1.610
L/D	463	402	402
L/A (m ⁻¹)	1.81 × 10 ⁵	1.28 × 10 ⁵	1.28 × 10 ⁵

^aValues taken from P. W. Garrison et al., "Natural Convection Boiling of Sodium in a Simulated FBR Fuel Assembly Subchannel," Vol. 4, pp. 1686-95 in *Proc. the Int. Meeting on Fast Reactor Safety Technology*, Seattle, Washington, August 1979.

^bCoil tube inner diameter is 3.05 mm.

^cValues include equivalent L/D due to bends in inlet coils.

3. LOOP INSTRUMENTATION

The instrumentation layout for the SBFV loop is also shown in Fig. 2.1. The instruments labeled TE are Chromel-Alumel (Type K) thermocouples (TCs). Those labeled FE are turbine flowmeters. The devices labeled PE are strain-gage pressure transducers, and the two RTDs on the glycerine system are shown as RT-36 and RT-37. There is also an additional RTD (RT-45) that measures the temperature of the reference junction for the Type K thermocouples, and there are two voltage supply monitors for the RTDs: one supply serves RT-36 and 37, and the second supplies RT-45. These three instruments are not shown.

Data collection is performed by a computer-controlled data acquisition system (DAS), capable of scanning at up to 10,000 points per second. Thirty-one of the instruments are connected to the DAS; these include all of the water loop thermocouples (TE-3-9, TE-11-18, TE-24, and TE-34); the four flowmeters (FE-1, 19, 22, and 30); the two pressure transducers (PE-2 and 10); the glycerine inlet, outlet, and tank temperatures (TE-26, 31, and 29); and all of the RTDs and their voltage supplies (RT-36, 37, 45, and the two supply monitors). The additional thermocouples on the glycerine loop are used as process instrumentation and are logged on a chart recorder. Bourdon tube pressure gages also monitor the pressures at the heated zone inlet and outlet.

The test section thermocouples are inserted directly into the water through channels in the annulus that open into the inner tube. These channels are sealed by epoxy resin. The pressure transducers measure from 0 to 41 kPa (gage) and are connected directly to the glass test section by short nipples. Flowmeters FE-1 and 19 are bidirectional turbine flowmeters capable of measuring flows as low as ~ 0.004 L/s. The bypass and glycerine flowmeters are also turbine meters but do not have bidirectional discrimination. The use of turbine flowmeters alleviates the problems experienced in Levin's water loop at MIT, since turbine meters are insensitive to pressure fluctuations.

The DAS is capable of recording 12 min of data on one seven-track magnetic tape. A line printer and a video display terminal (VDT) with a hard-copy unit are available for immediate viewing of selected data in either analog or digital form.

4. EXPERIMENTAL PROCEDURES

Three basic types of experiments were performed in the SBFV loop: forced convection, forced-to-natural convection transition, and natural convection. All three of these types of tests were performed in the original loop configuration (without the coil). Only natural convection experiments were run after the coil was installed.

Before each experiment, power to the glycerine tank was turned on. Preheat lines on the glycerine piping were also energized to decrease the viscosity of the glycerine enough to allow it to be pumped. Forced convection tests were run by maintaining pumped water flow throughout the experiment. The flow was controlled by adjusting valves on both the test section and the bypass. Closing valve HV-20 (see Fig. 2.1) introduced a greater pressure drop into the system, thereby decreasing flow, whereas closing valve HV-21 allowed less flow to bypass the test section, thereby increasing test section flow. Natural circulation tests were performed as closely as possible to the way in which sodium tests in the SBT facility were run. Once power was established to the test section, flow was allowed to develop as a result of the difference in thermal centers between the bypass and test section. The pump leg was valved out by closing HV-20. Forced-to-natural convection transition tests were run as an analog to tests conducted by Levin at MIT and described in Ref. 5. These tests were performed at low powers (less than 0.5 kW) to investigate boiling oscillations similar to those experienced during tests in the THORS facility. In these tests, the pump was run initially to establish a temperature profile in the test section. The heated section temperatures remained subcooled, as did the upper unheated zone. The pump was then turned off and the flow was allowed to coast down to natural convection. The bypass was kept closed to retard flow into the test section by means of the resistance of the stalled pump. In this manner, a small boiling zone was created at the end of the heated section while the unheated zone was extremely subcooled, producing a characteristic oscillatory pattern. Results from all three types of tests are presented in Sect. 5.

During a number of tests, high-speed (300–500 frames per second) motion pictures were taken of the test section boiling behavior. Most of the film was exposed using a close-up view (~150 mm) of the top of the heated section. However, motion pictures were also taken of the upper and lower ends of the test section, and one set was taken with an expanded view (~450 mm) of the top of the heated zone. When shown at normal projector speeds, these films permitted slow motion (~4.8%–8.0% real time) observation of the processes involved during oscillatory boiling. These motion pictures were quite valuable in data analysis.

5. EXPERIMENTAL RESULTS AND ANALYSIS

A large number of tests were performed in the SBFV loop to accommodate the various modes of testing and the change in loop configuration. As a result, a large amount of data was gathered during these tests. A representative sampling, showing all of the test modes in both loop configurations, is presented in this section. A listing and brief description of the tests discussed in the section are presented in Table 5.1; a similar listing for all tests performed in the SBFV is included in Appendix D.

Table 5.1 SBFV tests discussed in Sect. 5

Test No.	Run No.	Date	Length of test (s)	Approximate average power (kW)	Short description
102	106	2/17/82	30	1.48	Forced convection test with bypass open
103	101F1	3/1/82	60	1.44	Forced convection, bypass closed
21	2	11/12/81	120	0.31	Flow coastdown test
100	113	2/19/82	60	1.02	"No-flow" test — bypass valve closed
202	101F11	2/25/82	30	1.33	Natural circulation through pump leg
300	1052	5/11/82	180	2.46	Natural circulation through bypass
400	102	5/18/82	180	1.38	Natural circulation through bypass with inlet coil
400	107	5/21/82	180	1.74	Natural circulation through bypass with inlet coil

5.1 Forced Convection Tests

Forced convection tests were conducted only with the loop in its original configuration (without the coil). The tests were run with the bypass valve open and closed. The system behavior in these two cases differed markedly.

Test 102 Run 106 was a forced convection test with the bypass line open. The test section power was ~ 1.48 kW. Figures 5.1–5.7 present data for this run, with the instrument numbers listed as shown in Fig. 2.1. Two of the instruments did not operate properly. The outlet flowmeter (FE-19) produced a signal greater than the upper limit of its DAS gain;

Fig. 5.1. Test section flows and pressure for SBFV Test 102 Run 106.

Fig. 5.2. Bypass flow and glycerine flow and temperatures for SBFV Test 102 Run 106.

Fig. 5.3. Lower plenum temperature and glycerine line and tank temperatures for SBFV Test 102 Run 106.

Fig. 5.4. Upper plenum temperature and test section heated zone temperatures for SBFV Test 102 Run 106.

Fig. 5.5. Test section heated zone temperatures for SBFV Test 102 Run 106.

Fig. 5.6. Test section unheated zone temperatures for SBFV Test 102 Run 106.

Fig. 5.7. Test section unheated zone temperatures for SBFV Test 102 Run 106.

it therefore shows a flat line at its maximum, instead of the actual flow signal. In addition, riser thermocouple TE-13 was not connected properly during this test, and the instrument trace is not representative of the actual temperature at that point. All of the other instruments appear to have operated properly; however, since the bypass flowmeter (FE-22) is not a bidirectional meter, it registers a positive signal in reverse flow (downflow), which is not an accurate reading of the actual flow.

The oscillatory pattern observed on both the flowmeters and thermocouples is typical of the loop behavior during this type of test. Initially, a bubble forms at the top of the heated section. This normally results in a small, positive buoyancy-induced flow surge, such as that seen at ~15 s on FE-1 in Fig. 5.1. The vapor slug begins to grow and causes an increase in the two-phase pressure drop, causing the flow to decrease. This effect is related to the Ledinegg-type (static) pressure drop-flow instability. The flow continues to decrease, causing a further increase in pressure drop, until finally the test section contains almost totally vapor. At this point, the two-phase pressure drop begins to decrease, and the driving head of the system is sufficient to drive fluid back into the test section, creating the final surge in flow seen repeatedly (between 7 and 9, 16 and 18, 25 and 27 s) on FE-1. It is clear from these instrument traces that the expulsion occurs from the heated section outward in both directions, and reentry occurs from both ends of the test section back toward the center, since the outlet flow is positive when the inlet flow is negative and vice versa. While the outlet flowmeter reading cannot be considered accurate, it does reflect the fact that a large amount of vapor and very little liquid is flowing through the turbine during the expulsion phase of the oscillatory cycle; this is what causes the extremely high readings on the instrument.

The thermocouple traces also reflect the pattern of the oscillations; the lower thermocouples (TE-3, 4, 5) are well below saturation at the start of the expulsion, and the downflow of the two-phase mixture brings them rapidly to saturation, while the reentry of subcooled liquid drops them back into the subcooled range. The thermocouples at higher elevations in the heated zone show a much less dramatic swing in temperature. The riser thermocouples (TE-11 to 18) are heated only by the

upflow of hot fluid from the test section; their temperatures rise more slowly before the expulsion than the heated zone temperatures. The dip and rise shown by TE-17 and 18 after the reentry phase results from the passage of a bubble of uncondensed vapor and, probably, air initially dissolved in the water and stripped out during boiling, which remains after the lower and upper columns of liquid collide during reentry.

Forced convection runs were also performed with the bypass closed. Test 103 Run 101 is shown in Figs. 5.8–5.14. The power for this run was ~1.44 kW. The outlet flowmeter (FE-19) again overranged its DAS gain, as in the previous run. The lack of a signal on the bypass flowmeter

Fig. 5.8. Test section flows and pressures for SBFV Test 103 Run 101.

Fig. 5.9. Bypass flow and glycerine flow and temperatures for SBFV Test 103 Run 101.

Fig. 5.10. Lower plenum temperature and glycerine line and tank temperatures for SBFV Test 103 Run 101.

Fig. 5.11. Upper plenum temperature and test section heated zone temperatures for SBFV Test 103 Run 101.

Fig. 5.12. Test section heated zone temperatures for SBFV Test 103 Run 101.

Fig. 5.13. Test section unheated zone temperatures for SBFV Test 103 Run 101.

Fig. 5.14. Test section unheated zone temperatures for SBFV Test 103 Run 101.

(FE-22) confirms that the bypass valve was shut. All of the remaining instrumentation appears to have functioned properly.

While the general oscillatory pattern, shown by the pressure transducers and thermocouples, is similar to that observed in the prior run, there is a marked difference in the test section inlet flowmeter readings. In this case, there is no bypass into which fluid expelled from the test section can flow. Therefore, the large negative flows seen in the previous plots are absent here. Instead, the pump head must be overcome to force fluid back through the inlet. It can be seen that PE-2 and 10 in Fig. 5.8 show pressure oscillations much larger in magnitude than those in Test 102 Run 106, confirming this observation. The magnitude and duration of the negative flow pulses are much smaller than in the previous test because of the difficulty of forcing flow out of the test section. In fact it is possible that the mass flow into the test section was never actually negative. Because of the large density ratio of water to steam at atmospheric pressure, a large volumetric flow of vapor contains very little mass and can be balanced by a very small volumetric liquid flow. Since the inlet flowmeter is located well downstream of the lower plenum, it is conceivable that a core of vapor moving downward could cause the turbine to indicate a reversed flow, while a counterbalancing liquid mass flow along the wall of the test section would not be thick enough to offer any resistance to the turbine. The net inlet flow (as measured at the lower plenum) would then be either zero or slightly positive. It is difficult to confirm this phenomenon visually since the section around the flowmeter is not transparent. It should be noted that the water pump was turning at very low speeds during tests of this sort, and it is conceivable that fluid could be forced backward against the impeller. The upper plenum would then serve as the terminal point for the system, with the level rising slightly to accommodate the change in volume of the test section fluid during expulsion and reentry.

5.2 Flow Coastdown Tests

Flow coastdown tests were also conducted only in the initial loop configuration (without the coil). The objective of this type of test

was to produce oscillations similar to those in THORS facility sodium boiling tests. The tests were run at low power, and the procedure used was designed to produce only small-scale oscillations. Initially, the loop was maintained at low power and with forced convection; this kept both the heated section and the unheated riser well below saturation. The bypass was closed. To begin the test, the water pump was turned off. Flow to the test section then coasted down, to be maintained at a very low level because of the high resistance of the stalled pump. Boiling began at the end of the heated zone, but the remainder of the heated zone and the riser were both still subcooled. Because of the low power and high subcooling, the vapor was not allowed to expel large amounts of fluid; rather, the bubble tended to condense after a short expansion period. Oscillations ceased when the fluid heated up sufficiently to maintain steady natural circulation flow.

Test 21 Run 2 was a flow coastdown test run at an average power of ~ 0.31 kW. The power decreased considerably during the test, since the difficulty in maintaining low power in the loop required turning off the glycerine heaters. The power was initially ~ 580 W and remained at about that value until ~ 30 s. Between 30 s and 45 s, the power decreased to ~ 250 W. This power decrease was responsible for the cessation of oscillatory boiling. The calculated power, based on the glycerine flow and temperature difference, is shown as part of Fig. 5.16. (Figures 5.15–5.21 show the data from this test.) The inlet flowmeter (FE-1) did not function during this run; however, since vapor did not reach the upper flowmeter (FE-19) until the oscillations subsided, the readings from this instrument are regarded as providing a fairly accurate response to fluid oscillations. The initial flow was so large that it apparently overrode the ability of the flowmeter to register it, accounting for the anomalously low flow before the start of the coastdown. After the coastdown began, the flow dropped to within the flowmeter's range. Thus, after ~ 8 s, the reading is considered accurate until the oscillations subsided. The oscillatory pattern shown by the flowmeter is reproduced on the thermocouples, with the thermocouples near the largest temperature gradients showing the largest fluctuations. Data from this test are compared to sodium test data in Sect. 6.

Fig. 5.15. Bypass flow and test section outlet flow and pressures for SBFV Test 21 Run 2.

Fig. 5.16. Test section input power and glycerine flow and temperatures for SBFV Test 21 Run 2.

Fig. 5.17. Lower plenum temperature and glycerine line and tank temperatures for SBFV Test 21 Run 2.

Fig. 5.18. Upper plenum temperature and test section heated zone temperatures for SBFV Test 21 Run 2.

Fig. 5.19. Test section heated zone temperatures for SBFV Test 21 Run 2.

Fig. 5.20. Test section unheated zone temperatures for SBFV Test 21 Run 2.

Fig. 5.21. Test section unheated zone temperatures for SBFV Test 21 Run 2.

5.2.1 "No-flow" test

A final type of test was run only in the original configuration. In this test (Test 100 Run 113), both the bypass and test section inlet valves were shut. The power was ~1.05 kW. Cooling capability was provided by reflux cooling from the upper plenum. "Splashing" of fluid upward from the lower portion of the test section was also observed; however, the mechanism for this phenomenon is not well understood. Data from this test are presented in Figs. 5.22–5.28. Several comments must be made about these instrument traces.

Fig. 5.22. Test section flows and pressures for SBFV Test 100 Run 113.

Fig. 5.23. Bypass flow and glycerine flow and temperatures for SBFV Test 100 Run 113.

Fig. 5.24. Lower plenum temperature and glycerine line and tank temperatures for SBFV Test 100 Run 113.

Fig. 5.25. Upper plenum temperature and test section heated zone temperatures for SBFV Test 100 Run 113.

Fig. 5.26. Test section heated zone temperatures for SBFV Test 100 Run 113.

Fig. 5.27. Test section unheated zone temperatures for SBFV Test 100 Run 113.

Fig. 5.28. Test section unheated zone temperatures for SBFV Test 100 Run 113.

The outlet flowmeter once again produced a signal that overranged its DAS gain for a substantial portion of the test. This is an indication of a large vapor flow through the flowmeter. This vapor flow effectively blocked the reflux of liquid from the upper plenum between ~8 s and 25 s on Fig. 5.22 and for a number of shorter intervals thereafter; this is the phenomenon commonly called flooding. Note should be taken too of the inlet flowmeter readings. Even though there was no net inlet flow, the fluctuations in system pressure caused by the vapor efflux (and shown in Fig. 5.22 on PE-10 and 2) caused the height of the column of water left in the bottom of the test section to change. It is these

changes that are reflected in the flowmeter readings and not actual flows of liquid into the system.

The thermocouple readings during this test are also somewhat anomalous. Temperature rises, characteristic of dryout, are seen on the thermocouples in the heated section, even though these thermocouples are immersed in the fluid. This would seem to point to steam superheat in the heated zone. However, the riser thermocouples do not show an appreciable superheat (TE-13 once again failed to function properly). The probable explanation for this is that dryout did indeed occur in the heated section — a fact that was confirmed visually. Therefore, when the liquid evaporated, it left the thermocouple beads insulated from heat transfer to the system. Heat was then conducted down the thermocouple wire from the glycerine (through which the wire travels), and the bead temperature rose until the heat transfer from the wire to the steam was in equilibrium with the axial conduction from the glycerine. This behavior is also indicated by the fact that the bead temperatures peak very near the glycerine temperatures, as indicated by TE-RT 36 and 37.

A final observation should be made about the test section power. In most SBFV tests, the test section power remained fairly constant; the average powers reported for previous tests were representative of the power to the water for the duration of the run, with the previously mentioned exception of Test 21 Run 2. This is not the case in Test 100 Run 113. The test section power is plotted in Fig. 5.29. It begins at

Fig. 5.29. Test section input power for SBFV Test 100 Run 113.

~1.4 kW and drops to ~0.65 kW by the end of the test. This provides a clear illustration of the difference between a temperature-controlled and a power-controlled environment. As the test section dries out, the heat transfer coefficient drops at the inside wall. This increases the total resistance to heat transfer, and since the temperature difference remains almost constant ($T_{\text{glycerine}} - T_{\text{water}}$), the total heat transfer from the glycerine to the water and steam drops precipitously. In all of the other tests reported in this document, any dryout that occurred was of short duration and length and therefore did not affect the test section power input significantly.

5.2.2 Natural convection tests

Natural convection tests were run in both configurations in the SBFV, without and with the inlet coil. Before the coil was installed, tests were run with the natural circulation return path either through the stalled pump or the bypass line. After the coil was installed, only the bypass was utilized as the return line from the upper plenum.

Natural convection through the pump leg. Test 202 Run 101 was a combined forced and natural convection test. The initial files of data were acquired with forced convection similar to Test 103 Run 101 described above. The last four data files were then taken after the pump was turned off. The driving force for the flow was then the natural circulation head between the pump leg and the test section. The bypass valve was closed and the valve in the pump line was also partly closed. The restriction of this valve plus the stalled pump introduced a great deal of flow resistance into the system. The power was ~1.33 kW.

Data from this run are presented in Figs. 5.30–5.36. As in previous runs, the outlet flowmeter was pegged at its maximum output through much of the run. The behavior of the system is in some respects similar to the "no-flow" run (Test 100 Run 113). The outlet flowmeter signal implies that a large amount of vapor is leaving the test section, causing flooding to occur. Large pressure pulses are seen at ~5 s and 20 s, when the inlet flow is negative. This indicates that sufficient vapor pressure has built up inside the test section to force flow backwards against the resistance of the valve and pump. This behavior is further indicated

Fig. 5.30. Test section flows and pressures for SBFV Test 202 Run 101.

Fig. 5.31. Bypass flow and glycerine flow and temperatures for SBFV Test 202 Run 101.

Fig. 5.32. Lower plenum temperature and glycerine line and tank temperatures for SBFV Test 202 Run 101.

Fig. 5.33. Upper plenum temperature and test section heated zone temperatures for SBFV Test 202 Run 101.

Fig. 5.34. Test section heated zone temperatures for SBFV Test 202 Run 101.

Fig. 5.35. Test section unheated zone temperatures for SBFV Test 202 Run 101.

Fig. 5.36. Test section unheated zone temperatures for SBFV Test 202 Run 101.

by the thermocouple signals. At ~18 s, a large negative flow is indicated at the test section outlet, at a point when the pressure is quite low. The riser thermocouples TE-15, 16, 17, and 18 in Fig. 5.36 show drops in temperature at this time. All of these data combine to indicate a slug of liquid reentering the test section from the upper plenum and providing the cooling in the riser. This reduction of the available volume for vapor in the test section appears to be the reason for the sudden pressure pulse that immediately follows at ~20 s and expels liquid from both ends of the test section.

Natural convection through the bypass leg. The greatest number of tests in the SBFV loop were run in natural circulation through the bypass

lines. A full range of powers, from single-phase natural circulation to high-power boiling, was covered in both loop configurations. Four tests will be presented as representative of the low- and high-power boiling tests in each configuration.

Test 300 Run 105 was performed at a power of ~ 1.31 kW before the coil was installed. Data from this test are shown in Figs. 5.37–5.43. The oscillatory behavior shown by the system in this test is not unlike that shown in Test 102 Run 104 (forced convection with open bypass). The oscillations are quite regular in nature, and the cycle itself is reproduced well from oscillation to oscillation. The cycle proceeds through three discernible steps. First, a small vapor bubble forms, and

Fig. 5.37. Test section flows and pressures for SBFV Test 300 Run 105.

Fig. 5.38. Bypass flow and glycerine flows and temperatures for SBFV Test 300 Run 105.

Fig. 5.39. Lower plenum temperature and glycerine line and tank temperatures for SBFV Test 300 Run 105.

Fig. 5.40. Upper plenum temperature and test section heated zone temperatures for SBFV Test 300 Run 105.

Fig. 5.41. Test section heated zone temperatures for SBFV Test 300 Run 105.

Fig. 5.42. Test section unheated zone temperatures for SBFV Test 300 Run 105.

Fig. 5.43. Test section unheated zone temperatures for SBFV Test 300 Run 105.

its buoyancy causes the flow to accelerate slightly, resulting in the initial spike; it also causes the initial slight dip in test section thermocouple temperatures. Second, the bubble begins to grow, and the resulting two-phase friction quickly overcomes the buoyancy effect. This causes a rapid buildup in vapor generation, which in turn causes a pressure increase at the end of the heated zone that expels the liquid from both ends of the test section. This is reflected in the large negative spike on the inlet flowmeter and the large positive surge at the outlet. These flow surges cause both the heated zone and riser temperatures to rise rapidly to saturation as vapor fills the test section. The third step occurs after the test section is filled with vapor. The pressure falls until the head of the liquid in the bypass line is sufficient to allow reentry from both ends of the test section. This is indicated by the positive inlet and negative outlet flows. Since both the upper and lower plena are maintained in a subcooled condition, the reentry produces rapid decreases in test section temperatures throughout the heated zone and the riser. The only instrument in this data set that produced somewhat anomalous readings was the bypass flowmeter (FE-22). Since this flowmeter is designed to read only in one direction, negative flow (during the reentry phase) also produces a positive signal.

Test 300 Run 1052 was the highest power test run in the SBFV loop. The average power was ~2.46 kW. Data from this run are shown in Figs. 5.44-5.50. In the time between the previous test and this one, the outlet flowmeter ceased to function properly. Additionally, TE-8 in the heated zone and TE-31 in the glycerine line did not work properly during this test. The flow behavior during this test is noticeably different than in the previous run. The oscillations are much more rapid and less well defined. It appears from the flow and temperature readings that a column of liquid is oscillating rapidly at the lower end of the test section. The difference in the behavior of TE-6 and 7 indicates that the liquid column ends between those two elevations. The riser thermocouples show little, if any, reflux cooling, indicating that the riser is full of vapor and flooding is occurring at the upper plenum. The fluctuations in the riser thermocouple temperatures are most likely caused by changes in

Fig. 5.44. Bypass flow and test section pressures and inlet flow for SBFV Test 300 Run 1052.

Fig. 5.45. Glycerine flow and temperatures for SBFV Test 300 Run 1052.

Fig. 5.46. Upper and lower plenum temperatures and glycerine line and tank temperatures for SBFV Test 300 Run 1052.

Fig. 5.47. Test section heated zone temperatures for SBFV Test 300 Run 1052.

Fig. 5.48. Test section heated and unheated zone temperatures for SBFV Test 300 Run 1052.

Fig. 5.49. Test section unheated zone temperatures for SBFV Test 300 Run 1052.

Fig. 5.50. Test section unheated zone temperatures and input power for SBFV Test 300 Run 1052.

test section pressure. In contrast to the previous run, where the oscillatory cycle included boiling initiation, expulsion and reentry, and resultant subcooling, these data show that boiling never ceased entirely. The oscillatory cycle is caused by a complex interaction between the buoyancy, friction, and inertial pressure drops in the system. An expulsion of liquid from the inlet was followed by a rapid drop in test section pressure, allowing liquid reentry, subsequent compression of the remaining vapor, generation of additional vapor, and a pressure buildup causing an expulsion to begin the cycle again. All of the instrumentation confirms this cyclic behavior except for TE-5. Visual examination of the test section showed that the bead of this thermocouple did not

project far enough into the fluid stream to measure the actual fluid temperature. Instead, the bead is shielded enough so that it probably registered a temperature close to that of the inner test section wall at that elevation.

Test 400 Run 102 was performed after the loop was modified to include the coil at the inlet. The test power was ~ 1.38 kW. Data from this run are shown in Figs. 5.51–5.57. Here again, the outlet flowmeter did not function correctly and has been omitted. In addition, this run was performed in a different test section from the series 300 tests, and the lower three heated zone thermocouples did not extend into the test

Fig. 5.51. Bypass flow and test section pressures and inlet flow for SBFV Test 400 Run 102.

Fig. 5.52. Glycerine flow and temperatures for SBFV Test 400 Run 102.

Fig. 5.53. Upper and lower plenum temperatures and glycerine line and tank temperatures for SBFV Test 400 Run 102.

Fig. 5.54. Test section heated zone temperatures for SBFV Test 400 Run 102.

Fig. 5.55. Test section heated and unheated zone temperatures for SBFV Test 400 Run 102.

Fig. 5.56. Test section unheated zone temperatures for SBFV Test 400 Run 102.

Fig. 5.57. Test section unheated zone temperatures and input power for SBFV Test 400 Run 102.

section sufficiently far to provide an accurate reading of fluid temperature; instead, they behaved similarly to TE-5 in Test 300 Run 1052 in recording a temperature close to that of the test section inner wall.

A number of differences are immediately apparent when data from Test 300 Run 105 are compared to these data. Although both tests are at approximately the same power, the inlet flow is much smaller in Test 400 Run 102, both in the maximum amplitude during oscillations and in the average value over the course of the test. This behavior is caused by two factors. First, the coil introduces a large additional resistance to the loop, since its length is ~ 2.8 m and the inner diameter is 3.05 mm. This serves to reduce the average flow because of increased friction. Second, the coil also creates a large inlet inertance in the system. The inertance, defined as $\rho_f L/A$, is the term in the momentum equation that multiplies the change in flow with time. During steady flow, this term is zero. However, in oscillatory flow the inertial pressure drop can represent a significant portion of the total system pressure drop, further reducing the flow. Physically, the inertance behaves in a manner similar to that of an electrical inductance and resists rapid changes in flow. This also accounts for the observed change in the oscillatory pattern seen in Test 400 Run 102 — the oscillations themselves are much less sharply defined. The pulsations tend to be "stretched out" by the increased loop inertance. This phenomenon will be discussed further in later sections.

The difference in the response of the pressure transducers is also quite striking. The pressure oscillations are much less regular than in the previous tests, and the inlet transducer (PE-2) shows much wider changes than previously. This is explained by the added pressure required to force flow back through the increased resistance and inertance of the coil.

Although the lower three heated zone thermocouples did not read true fluid temperatures, TE-6 appears to provide an accurate reflection of flow behavior at low elevations. The temperature oscillation pattern agrees quite well, as before with the flow oscillation pattern, with heating occurring during the expulsion phase of the oscillation, and with rapid cooling during the reentry phase. The pattern also bears out the

smoother oscillatory behavior, and the lowest temperature reached during the reentry phase is not as cold as in the Test 300 run, indicating a slower rate of upflow. From the upper level thermocouples, it appears that reentrant flow never reaches the end of the heated section while it is subcooled. As previously noted, the outlet flowmeter did not work properly. However, visual observation showed behavior similar to that in previous tests. Since no additional resistance or inertance was added at the upper end of the test section, the rate of expulsion and reentry was about the same as in previous tests. However, the lower overall flow resulted in a much increased production of vapor in the test section, which controlled the upper flow behavior as well. Downward spikes in the upper riser thermocouples indicate periods of reentry from the upper plenum, but these spikes are gone by the time TE-13 is reached. The high rate of vapor flow tended to cause flooding at the upper plenum, only occasionally allowing small amounts of fluid back into the test section, which were then quickly swept out again before a column of liquid could form to keep the region subcooled for more than a very short time.

The last natural circulation test to be discussed is Test 400 Run 107. Also performed in the modified loop, this was the highest power test to be run after the coil was installed, at 1.74 kW. Although this is about 30% lower than the corresponding high-power test in the original configuration (Test 300 Run 1052), the lower rate of flow made the rate of vapor production at least as high as in that run. Data from this test are shown in Figs. 5.58-5.64. The instrumentation conditions were the same as those in Test 400 Run 102.

The effect of the higher inlet inertance and resistance are both immediately evident once again by virtue of the reduced inlet flow and altered oscillation behavior. The general appearance of the oscillatory pattern as compared to the lower power test shows similar characteristics to the two Test 300 runs — the high-power run shows a more rapid rate of oscillation without the intervals of low, relatively steady flow between spikes as shown in the low-power run. The pressure traces for this run also confirm again the behavior of the modified system — the magnitudes of the oscillations are larger because of the higher pressure required to overcome increased frictional and inertial forces.

Fig. 5.58. Bypass flow and test section pressures and inlet flow for SBFV Test 400 Run 107.

Fig. 5.59. Glycerine flow and temperatures for SBFV Test 400 Run 107.

Fig. 5.60. Upper and lower plenum temperatures and glycerine line and tank temperatures for SBFV Test 400 Run 107.

Fig. 5.61. Test section heated zone temperatures for SBFV Test 400 Run 107.

Fig. 5.62. Test section heated and unheated zone temperatures for SBFV Test 400 Run 107.

Fig. 5.63. Test section unheated zone temperatures for SBFV Test 400 Run 107.

Fig. 5.64. Test section unheated zone temperatures and input power for SBFV Test 400 Run 107.

The response of the test section thermometry shows some interesting behavior. The upper level heated section thermocouples indicate a constant state of saturation, so that the reentrant flow never reached that level. While TE-4 and 5 do not register the actual fluid temperature, they do show intermittent temperature spikes, which probably indicate wall dryout at those elevations. A continued temperature rise as in Test 300 Run 1052 is not seen, indicating that enough liquid is splashing upward during the reentry phase to rewet the wall. The riser thermocouples showed fluctuations consistent with pressure changes, but no spikes indicating reentry from the upper plenum can be seen. Clearly, the rate

of vapor production is so high that flooding is once again occurring at the upper plenum for the entire 3 min of data.

The data presented in this section represent only a small fraction of what has been acquired using this system; however, all of the important phenomena that have been observed during testing are covered in these nine runs.

During SBFV testing in both loop configurations, computer modeling has been performed, both to attempt to match the SBFV data and to explore the effect of changing various parameters on predicted loop behavior. A detailed description of the computer model and examples of the output are presented in Sect. 7. Results of an analytical study of constant temperatures vs constant power boundary conditions are discussed in Appendix C.

6. COMPARISON OF SBT AND SBFV DATA

The development of the SBFV loop and experimental program has had two major objectives: (1) the direct observation of processes involved in boiling oscillations and (2) comparison of this oscillatory behavior to that observed during sodium testing in the SBT and THORS facilities.

Most of the emphasis has been on comparisons between the SBT and SBFV tests, since the geometries of the two loops, after modification of the SBFV by the addition of the inlet coil, are almost identical (see Table 2.1). As similar as the two loops are geometrically, comparison of data from sodium and water tests is quite limited; the only instrument readings that can be directly related are inlet flow and pressure. There are several reasons for this fact. First, the SBT test section is fabricated from thick-walled Hastelloy-X tubing, and thermocouples are fastened to the outside of the test section wall. The thermal inertia of the tubing was so large that rapid fluctuations in fluid temperatures could not be detected. The SBFV thermocouples, which are in direct contact with the working fluid, respond to such fluctuations accurately, since the thermal inertia of the thermocouple bead is almost zero. Second, the placement of pressure transducers in the SBT means that the only common measurement point is the test section inlet. Third, the flowmeters in the two loops are of different types. The flowmeters on the SBT loop are permanent magnet-type devices. These flowmeters respond only to the electromagnetic impulses created by liquid flow; therefore, vapor flow will not produce a signal. Aside from an occasional balkiness, the turbine flowmeters on the SBFV loop produce a signal regardless of whether vapor or liquid is passing through them. In fact, vapor flow produces a very large signal because there is relatively little resistance to rotation of the turbine. Since the outlet flowmeters in both loops see substantial amounts of vapor flow, the two signals are not likely to be closely related. The inlet flowmeters, however, see only liquid in both loops. There is a slight difference in location — the SBT facility meter is upstream of the inlet coil, while the SBFV loop meter is downstream of the coil. The effect of this difference will be

discussed later in this section. Despite the locational difference, the signals of the two flowmeters should provide a fairly accurate indication of the amount of similarity in the behavior of the two loops, particularly when coupled with the inlet pressure readings.

The one fundamental difference in the two loops, aside from the working fluid, is that the SBFV loop is an open system, while the SBT loop is a closed one; that is, the SBFV upper plenum is open to the atmosphere, while pressure in the SBT upper tank is maintained in a sealed system by argon gas. The result of this difference is probably small; however, it should be realized that changes in level in the upper plenum of the SBFV have no effect upon the pressure at the free liquid surface, while similar changes in level in the sodium system will, through compression and expansion, alter the free surface pressure slightly.

As previously mentioned, several flow coastdown tests were also performed in the SBFV loop, as an analog to tests run in the THORS facility. These were done before the installation of the inlet coil, since the THORS facility has no such device. Comparison between the THORS loop and the SBFV loop is less direct, because the THORS test section is a multi-pin simulated LMFBR fuel assembly, not a single tube. However, the lengths and the relative location of the heated and unheated zones are similar in the two loops. The instrument readings that are used in the comparison of these data are the inlet pressure and outlet flow. In these water tests, the inlet flowmeter did not function; however, the oscillations were of such a small scale that no vapor reached the outlet flowmeter in either loop to interfere with the signals. The comparison of readings from these instruments should therefore provide an adequate measure of the similarity in loop behavior. The intent in the THORS-SBFV comparisons is oriented more toward finding if a qualitative similarity exists phenomenologically, rather than toward making a direct quantitative comparison of data, as is done with the SBT facility and SBFV loop.

THORS Bundle 6A was a 19-pin simulated LMFBR fuel assembly of Fast-Flux Test Facility (FFTF) design. A large number of flow coastdown boiling tests were run during the Bundle 6A test program. Test 72A Run 101

was run at a bundle power of ~ 185 kW, or ~ 9.7 kW/pin. The flow was initially ~ 0.23 L/s; the flow at the end of the boiling transient was ~ 0.07 L/s. Outlet flow and inlet pressure data for this test are shown in Fig. 6.1. Outlet flow and inlet pressure for SBFV Test 21 Run 2, described in the previous section, are repeated here in Fig. 6.2. The similarity in the boiling pattern is clearly evident, showing a characteristic "envelope" shape. This appears to confirm the similarity of the processes controlling this type of oscillatory behavior: the formation of a

Fig. 6.1. Test section outlet flow and inlet pressure for THORS Bundle 6A Test 72A Run 101.

Fig. 6.2. Test section outlet flow and inlet pressure for SBFV Test 21 Run 2.

small vapor area at the top of the heated zone that starts to expand but that is forced to contract because of condensation in the subcooled regions of the test section, thereby resulting in a repeated oscillatory pattern. To illustrate that this is not an isolated phenomenon, the test section inlet flow from Bundle 6A Test 71H Run 101 is also shown in Fig. 6.3. This test was run at ~ 6.8 kW/pin, with initial and reduced flows of ~ 0.11 L/s and ~ 0.02 L/s, respectively. The characteristic envelope pattern of the boiling oscillations is again evident; flow reversal at the inlet, which was visually observed in the SBFV (though instrument data to support the observation are not available), is also seen in the THORS test.

Data from the SBT facility tests are presented in Ref. 2. In all, 22 natural circulation tests were run, under conditions ranging from single-phase flow to boiling and dryout. The power range reported for these tests is 300–1700 W. (Power measurement in the SBT was a source of considerable uncertainty; this is discussed in more detail in Appendix B.) As an example of SBT loop boiling behavior, Fig. 6.4 shows test section inlet flow and pressure in SBT Test 129R1, a natural circulation boiling test at a power of ~ 1.3 kW. The oscillatory nature of boiling in the SBT loop is quite evident and provides a starting point for comparison of data from the water and sodium loops.

Fig. 6.3. Test section inlet flow for Test 71H Run 101, THORS Bundle 6A.

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Fig. 6.4. Test section (a) inlet flow and (b) pressure for SBT Test 129 Run 1, natural-circulation test at ~ 1.3 kW.

It is immediately clear that the boiling behavior seen in the SBFV loop prior to installation of the coil does not provide a good match to the behavior of the SBT facility. The maximum amplitude of the water oscillatory flow (as shown in Fig. 5.37 during Test 300 Run 105, for example) is about four times that of the maximum amplitude of the sodium oscillations. Average magnitudes of test section flow are also roughly in that proportion. The inlet pressure also shows considerable dissimilarities. Comparison of sodium and water data should therefore be limited to those tests run after the installation of the inlet coil.

The test section inlet flow and pressure from Test 400 Run 102 are reproduced in Fig. 6.5. When compared to the data from SBT Test 129R1, a number of similarities are apparent. The rates of natural circulation

Fig. 6.5. Test section (a) inlet flow and (b) pressure for SBFV Test 400 Run 102, natural-circulation test at ~ 1.4 kW.

flow, both the average and the maximum, are in the same order of magnitude. The slightly higher flow in the water system is a result mainly of the slightly larger diameter of the test section. The oscillatory frequencies are also in fairly good agreement, as is the general shape of the pressure traces. Although there are discrepancies in some of these parameters, a number of them can be explained in terms of scaling factors (see Appendix A). The major point of disagreement in the sodium data vis-a-vis the water data is in the large number of apparent flow reversals in the water system, compared to the low number of such occurrences in the sodium loop. (This discrepancy is addressed in Appendix B, where errors and uncertainties are discussed.)

A comparison may also be made between higher power runs in the two loops. The test section inlet flow and pressure for SBT Test 128R1 are

shown in Fig. 6.6. This was a dryout test at ~ 1.7 kW; the occurrence of dryout late in the plotted data (at ~ 230 s) caused a power interlock to be tripped because of high test section temperatures, causing the rather anomalous behavior seen at the end of the test. Although dryout was also observed in a number of SBFV tests, the test section temperature is limited by the glycerine temperature and a similar interlock is unnecessary. The test section inlet flow and pressure from SBFV Test 400 Run 107 is reproduced in Fig. 6.7. Once again, a general agreement is seen in the magnitudes of the flows, as well as in the shape of the flow and pressure traces. In addition, the anomalous flow reversals noted in the lower power water test are also present in this test.

The sodium loop, in general, displays a more complex behavior during instabilities than does the water loop. For instance, Fig. 6.8 shows data

Fig. 6.6. Test section inlet flow and pressure for SBT Test 128 R1, natural circulation test at ~ 1.7 kW.

ORNL-DWG 82-6493 ETD

Fig. 6.7. Test section inlet flow and pressure for SBFV Test 400 Run 107, natural circulation test at ~ 1.7 kW.

ORNL-DWG 82-6491 ETD

Fig. 6.8. Test section inlet flow and pressure for SBT Test 120 R1, natural circulation test at ~ 1.5 kW.

from SBT Test 120R1, a boiling test at ~ 1.5 kW. Here, between 30 s and 40 s and again between ~ 55 s and 80 s, the inlet flow and pressure display a behavior very similar to those in the water loop tests. However, between 20 s and 30 s and then from 40 s to ~ 55 s, a more rapid oscillatory pattern is seen with a slightly higher rate of average flow. Data from the void detectors used on the SBT loop seem to indicate that this is a result of a change from a high-flow/low-quality mode to a low-flow/high-quality one. This type of behavior has not been seen in similar tests in the SBFV loop, and the reasons for the apparently random flip-flops in system behavior are unknown. (This topic is also addressed in Appendix B.)

In spite of the disparities that have been discussed, the water data indicate that the processes occurring during boiling oscillations in the two systems are related and that valuable information on sodium boiling behavior can be obtained by using a properly scaled, nonmetallic fluid system.

7. ANALYTICAL MODELING

In order to analyze SBFV data, the computer program LOOP-W has been developed. This program models the upper and lower plenum tanks of the SBFV loop, as well as the three legs connecting them. The flow area, the hydraulic diameter, and the node length may be different for each leg, but are constant throughout the leg. Each leg may contain up to 100 nodes. The volume of the upper and lower plena can be varied, as well as the temperature of the water in each tank. Heat exchangers in the plena are modeled with the options of constant temperature or constant heat removal. Commonly, the constant temperature option was used in modeling the SBFV data. Only one-dimensional flows (in the axial direction) are considered in each leg. This is considered to be a valid assumption because of the extremely small diameter of the test section. The same consideration applies to the other legs.

The two-phase flow is modeled assuming thermodynamic equilibrium conditions — a realistic assumption since superheated vapor does not occur simultaneously with liquid water in these experiments. This approach is much simpler than a two-fluid model, and it has been found to give good agreement with the experimental data.

The following equations are solved.

Mixture continuity:

$$\frac{\partial}{\partial t} \rho_m + \frac{\partial}{\partial z} \rho_m w = 0 , \quad (7.1)$$

where the mixture density is given by

$$\rho_m = \rho_{f,sat}(1 - \alpha) + \rho_{g,sat}\alpha . \quad (7.2)$$

Mixture momentum:

$$\begin{aligned} \frac{\partial}{\partial t} (\rho_m w) + \frac{\partial}{\partial z} (\rho_m w w) + \frac{\partial P}{\partial z} - \rho_m g + \frac{1}{dz} \\ \times (\Delta P_F + \Delta P_K - \Delta P_{pump}) = 0 , \end{aligned} \quad (7.3)$$

with the friction losses given by

$$\Delta P_F = \frac{64}{Re} \frac{L}{D} \frac{\rho_m w^2}{2} \quad (7.4)$$

for laminar flow ($Re < 2000$) and

$$\Delta P_F = 0.1582 \frac{L}{D} \frac{\rho_m w^2}{2} Re^{-0.25} \quad (7.5)$$

(Blasius formula) for turbulent flow ($Re > 2000$).

The pressure drop across the valves is modeled as

$$\Delta P_K = K \rho_m w^2, \quad (7.6)$$

where K is input.

Mixture energy:

$$\frac{\partial}{\partial t} (\rho_m e) + \frac{\partial}{\partial z} (\rho_m w e) + \frac{\partial (Pw)}{\partial z} + q - \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) = 0. \quad (7.7)$$

The viscous forces are neglected in the momentum equation. Also, the viscous dissipation, the gravitational potential energy, and the fluid kinetic energy are neglected in the energy equation, since their values are very small compared to other terms in the energy equation.

In order to eliminate the specific internal energy from Eq. (7.7), the following relationship is used:

$$h = e + Pv = e + P/\rho_m, \quad (7.8)$$

and Eq. (7.7) is converted into

$$\frac{\partial}{\partial t} (\rho_m h) - \frac{\partial P}{\partial t} + \frac{\partial}{\partial z} (\rho_m w h) + q - \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) = 0. \quad (7.9)$$

The heat input radially into the test section q is calculated by using a finite-difference solution of the heat conduction equation in the Pyrex tube that surrounds the heated zone of the test section. Ten nodes in

the radial direction are considered for each axial node of the test section (Fig. 7.1). Axial conduction inside the glass is neglected. Appropriate heat transfer coefficients are used for the glycerine side (single-phase) and for the water side, where both single- and two-phase flows are present. The Dittus-Boelter correlation⁶ is used for the glycerine side and for the water side under single-phase forced convection conditions. Under two-phase boiling conditions, the Chen correlation⁷ is used. A natural convection heat transfer coefficient is used outside the unheated zones of the test section. The temperature of the glycerine is an input quantity, and it is assumed to be constant during the calculation. The temperature in the fluid is calculated as a function of the specific enthalpy by the following relations:

$$T = h/c_{p,f} \text{ for } h \leq h_{f,sat} \text{ or } T \leq T_{sat} , \quad (7.10)$$

$$T = T_{sat} \text{ for } h_{f,sat} \leq h \leq h_{g,sat} , \quad (7.11)$$

$$T = h/c_{p,g} \text{ for } h > h_{g,sat} . \quad (7.12)$$

The quality is obtained by

$$x = \frac{h - h_{f,sat}}{h_{g,sat} - h_{f,sat}} , \quad (7.13)$$

where the saturation-specific enthalpies are calculated as a function of

Fig. 7.1. Radial nodes used in the heated zone of the SBFV test section.

the pressure. The void fraction is calculated by

$$\alpha = \frac{1}{1 + \frac{1-x}{x} \frac{\rho_{g,sat}}{\rho_{f,sat}} S} , \quad (7.14)$$

where the slip ratio S is obtained as a function of the quality

$$S = 4.3 + 79x \quad \text{for } x > 0.01 , \quad (7.15)$$

$$S = 1 + 409x \quad \text{for } x < 0.01 . \quad (7.16)$$

Equations (7.5) and (7.6) were obtained by fitting the experimental data of Sher given in Ref. 8. Vapor and liquid velocities were also estimated from some of the high-speed movies, and slip ratios between 10 and 30 were estimated. These values are within the range of Eq. (7.15) for the low qualities present during most of the transients.

Another expression, similar to Eq. (7.16), was also investigated:

$$S = 1 + Cx . \quad (7.17)$$

Good agreement with experimental data was also obtained using this equation with $C = 200$. A sensitivity study was performed varying the value of the constant C ; it has been reported in Ref. 9.

The numerical solution of the equations of continuity of mass (7.1), momentum (7.3), and energy (7.9) is based on the SIMPLE algorithm.¹⁰ In this algorithm, the conservation of momentum equation for the mixture is solved first, using initial estimates for the pressure and for the velocity. The static pressure head is used as the initial value for the pressure. An estimated initial value for the velocity must be input. If values from previous calculations exist, these values are used as estimates for the present calculation. Then, the equation of continuity of mass (7.1) is solved to obtain pressure and velocity corrections for the momentum equation. In the next step, the energy equation (7.9) is solved. This procedure is repeated until convergence is obtained.

The convective terms are approximated by upwind finite differences to improve numerical stability. The numerical method is fully implicit; therefore, the time step size is not limited by the Courant condition. It has been observed that convergence has actually been obtained sooner for larger time steps. The main difficulty of the method is the determination of the under-relaxation factor to be used for the velocity and pressure corrections. If this factor is too large, divergence results. However, if the factor is too small, too many iterations are needed to obtain the converged solution. It has been found that the smaller the time step, the smaller the under-relaxation factor should be. For time steps between 50 ms and 100 ms, under-relaxation factors around 0.05 have been found adequate.

The total power input into the water is calculated by

$$q_{in} = \sum_{j=1}^n h_{in}^j A_{in} (T_{in}^j - T_w^j) , \quad (7.18)$$

where the summation applies over the axial nodes considered in the heated part of the test section. The area between the internal surface of the glass tube and the water is calculated by

$$A_{in} = 2\pi r_{in} L , \quad (7.19)$$

where $L = 0.16$ m is the node length. The power removed from the glycerine through the outside surface of the glass tube is calculated by

$$q_{out} = \sum_{j=1}^n h_{out} A_{out} (T_{gl} - T_{out}^j) , \quad (7.20)$$

with

$$A_{out} = 2\pi r_{out} L . \quad (7.21)$$

This power can also be calculated from the experimental data by a heat balance on the glycerine side of the loop using the equation

$$q_{gl} = Q_{gl} \rho_{gl} c_{p,gl} (T_{gl,inlet} - T_{gl,outlet}) . \quad (7.22)$$

The power calculated by this expression includes the heat losses from the glycerine into the environment. The temperatures of the glycerine are measured by resistance temperature devices located at the test section inlet (RT-37 shown in Fig. 2.1) and outlet (RT-36). The glycerine flow, Q_{g1} , is measured by flowmeter FE-30.

The first test modeled using LOOP-W was Test 102 Run 106, a forced convection test with the bypass line open. Figure 7.2 shows the number of nodes used in each leg — 18 in the test section (2 upstream of the heated section, 6 in the heated part, 10 in the riser), 9 in the bypass, and 22 in the pump leg. The following values were used for the input variables: upper plenum temperature 54°C, lower plenum temperature 27°C, glycerine temperature 180°C, and glycerine flow 0.12 L/s. Calculated values for the inlet and outlet flow, bypass flow, and temperatures at the beginning (TE-3) and at the end (TE-9) of the heated part of the test section and at the beginning (TE-11) and at the end (TE-18) of the unheated riser, as well as the pressures at the entrance (PE-2) and at the exit (PE-10) of the heated part of the test section are shown in Fig. 7.3. (Refer to Fig. 7.2 for locations.) The period of the oscillations was 9 s. For comparison purposes, 30 s of data, taken at the same locations, are shown in Fig. 7.4. The amplitude of the calculated oscillations is smaller than the experimental values, due probably to an imperfect modeling of the pump head vs flow. In general, though, calculated and experimental values are in good agreement.

The second test modeled was Test 21 Run 2, the flow-coastdown test as described in Sect. 5. Only two legs (test section and pump) were considered, with 18 and 11 nodes, respectively (Fig. 7.5). The temperatures for the lower and upper plena were 30°C and 33°C, respectively. The glycerine temperature was 123°C, and the heat transfer coefficient between the glycerine and the glass was 500 W/m²·°C. Forced convection was obtained at a steady-state flow of 0.0212 L/s through the test section using a ΔP for the pump of 45,000 Pa. At 8 s, the power to the pump was cut, and the flow decreased to a very low value. At around 28 s, boiling started and boiling stopped at 42 s, 3 s earlier than the experimental data. Figure 7.6 shows the calculated inlet and outlet flows, as well as the experimental outlet flow (reading of the outlet flowmeter FE-19).

Fig. 7.2. SBFV noding scheme for LOOP-W simulation of Test 102 Run 106.

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Fig. 7.3. LOOP-W calculated test section flows, pressures and temperature for SBFV Test 102 Run 106.

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Fig. 7.4. Experimental test section flows, pressures, and temperatures, corresponding to LOOP-W calculations for SBFV Test 102 Run 106.

Fig. 7.5. SBFV noding scheme for LOOP-W simulation of Test 21 Run 2.

Fig. 7.6. Test section outlet flow (experimental) for SBFV Test 21 Run 2, and calculated inlet and outlet flows by LOOP-W.

It can be seen that the reading of this flowmeter during the first 8 s of the transient is much lower than the calculated value because of an inaccurate flowmeter reading during these 8 s.

Although the boiling initiation and boiling termination was adequately reproduced by the computer program, only the first two boiling oscillations were predicted by the program. These oscillations correspond to the boiling process, with bubbles forming in the heated part of the test section and being condensed in the unheated part of the riser.

Calculated temperatures at the beginning and end of the heated section and the unheated riser are shown in Fig. 7.7. They agree well with the experimental values. The power calculated during the forced convection part of the transient was 521 W, and the power after boiling stopped was 228 W, in agreement with the experimental data (580 W during the first 30 s, decreasing to 250 W after 45 s).

Fig. 7.7. Temperatures from various test section thermocouples for SBFV Test 21 Run 2 (experimental and calculated by LOOP-W). Refer to Fig. 7.5 for instrument locations.

Figures 7.8 and 7.9 show comparisons between the readings of the two pressure transducers (PE-2 and PE-10) and the pressure calculated at nodes 3 and 10 of the test section leg in Fig. 7.5. They also show good agreement.

Fig. 7.8. Experimental data and LOOP-W calculation for pressure at heated zone inlet in SBFV Test 21 Run 2.

Fig. 7.9. Experimental data and LOOP-W calculation for pressure at top of test section heated zone in SBFV Test 21 Run 2.

Test 300 Run 105, a natural convection test with the bypass leg open (and the pump leg closed), was also modeled using a nodalization similar to the one of Fig. 7.5 (a bypass leg with nine nodes was used instead of a pump leg). The following input conditions were used: upper plenum temperature 42°C , lower plenum temperature 22°C , glycerine temperature 170°C , glycerine flow 0.15 L/s , and glycerine-glass heat transfer coefficient $5200\text{ W/m}^2\cdot^{\circ}\text{C}$. Calculated results for a 30-s period are shown in Fig. 7.10; they can be compared with the experimental data

Fig. 7.10. LOOP-W calculated test section flows, pressures, and temperatures for SBFV Test 300 Run 105.

in Fig. 7.11. The readings from the outlet flowmeter (FE-19) are not accurate due to a problem with the instrument gain and because turbine flowmeters do not record data accurately under two-phase flow conditions. The observed period of the oscillations was 6.1 s, in agreement with the calculated period. Figure 7.12 shows the power calculated by Eq. (7.18) (input power into the water), Eq. (7.20) (input power into the test

Fig. 7.11. Experimental test section flows, pressures, and temperatures corresponding to LOOP-W calculations for SBFV Test 300 Run 105.

Fig. 7.12. Power calculated by Eqs. (1), (3), and (5) for SBFV Test 300 Run 105.

section from the glycerine), and Eq. (7.22) (input power based on glycerine inlet and outlet temperatures and flow).

The average input power, as calculated by either Eq. (7.18) or Eq. (7.20), is 1.13 kW. The high-power peaks (in excess of 2 kW) correspond to the reentry phases of the transient, when the tube is rewetted with water coming from both the top and bottom plena. These peaks also appear in the values obtained with Eq. (7.20), but they are not so sharp. The low-power values correspond to the beginning of the boiling process, as the steam removes less power than the liquid water. It can be seen how the input power and the inlet flow have similar shapes (Fig. 7.13). Figure 7.14 shows the calculated heat transfer coefficient at the internal surface of the glass wall at the third node from the beginning of the heated part of the test section (the complete heated part has six

Fig. 7.13. Calculated input power into the water and calculated inlet flow for SBFV Test 300 Run 105.

Fig. 7.14. Calculated heat transfer coefficients for SBFV Test 300 Run 105.

nodes). The figures also show a similarity in the shapes of the curves for power and heat transfer coefficients.

The test section power derived from a heat balance on the glycerine for this test was 1.30 kW. The discrepancy between the analytically and experimentally obtained values, about 13%, is explained by a number of factors. The data, as previously explained, represent an average of digitized values of flow and temperature differences with their inherent experimental errors. In addition, heat losses to the environment are not accounted for in the glycerine heat balance. In the analytical calculation, uncertainties exist in heat transfer coefficients, glass and liquid properties, etc.; the analytical calculation does account only for the heat transfer into the water. A sample calculation of losses to the environment, by radiation and convection, is included in Appendix B, along with a more detailed discussion of uncertainties. It is worthwhile to note that the estimate of convective and radiative losses is of roughly the same order of magnitude as the above analytical-experimental discrepancy; in fact, the primary reason for the discrepancy is most probably these losses. Considering the uncertainties in both the experimental and analytical calculations, the LOOP-W code appears to provide a good estimate of test section power input.

The oscillations in the heat transfer coefficient around the value of $2000 \text{ W/m}^2 \cdot ^\circ\text{C}$ in Fig. 7.14 were due to discontinuities between values calculated for laminar and turbulent flow conditions. The flow in that region was near the transition between laminar and turbulent, and the computer program switched between the two regimes during consecutive time steps. The same oscillations can also be seen in the power calculated by Eq. (7.18) around the value of 1.1 kW (Fig. 7.12). This power is calculated by utilizing the previously mentioned heat transfer coefficient.

Finally, Test 400 Run 102, with the modified loop including the coil at the inlet, was also modeled. Figure 7.15 shows the nodalization used; 33 nodes are in the test section (0.16 m in length each), with 15 of them located horizontally in order to simulate the inlet coil. Also, to account for the higher friction losses in the coil, a coefficient of $K = 10$ was used for the inlet valve at the entrance of the coil. The

Fig. 7.15. SBFV noding scheme for LOOP-W simulation of Test 400 Run 102.

bypass leg was modeled with nine nodes (0.32 m in length each). Additional input values used were: upper plenum temperature 43°C , lower plenum temperature 26°C , glycerine temperature 174°C , glycerine flow 0.15 L/s , and glycerine-glass heat transfer coefficient $5200.0\text{ W/m}^2\cdot^{\circ}\text{C}$. Calculated results are presented in Fig. 7.16 and experimental data in Fig. 7.17. Comparing both figures, the following observations can be

Fig. 7.16. LOOP-W calculated test section flows, pressures, and temperatures for SBFV Test 400 Run 102.

Fig. 7.17. Experimental test section flows, pressures, and temperatures corresponding to LOOP-W calculations for SBFV Test 400 Run 102.

drawn: good agreement was obtained for the inlet flow (FE-1), fair agreement for the temperatures (TE-6, 17, and 18) and for the pressures (instruments PE-2 and 10), and disagreement for the temperatures measured at the beginning of the heated section (TE-3), at the end of the test section (TE-9), and at the beginning of the unheated riser (TE-11).

Posttest examination of these thermocouples (TE-3, 9, and 11) revealed that they were not introduced sufficiently into the test section and that they were in contact with the glass instead of being in contact with the water. Also, the reading of the outlet flowmeter (FE-19) was in error and therefore is not displayed in Fig. 7.17.

Although the inlet coil was modeled in a very simple way, using a horizontal portion of pipe of the same length and an increased friction loss using an inlet valve, the agreement obtained between experimental and calculated values is fair. It should be mentioned here that the ratio of computer (CPU) time to problem time in this last test was 117, much higher than for other tests modeled without the coil, where this ratio varied from 25 to 50.

8. CONCLUSIONS AND FUTURE PLANS

Based on the discussion in the two previous sections, a number of conclusions can be drawn.

1. The design of the Simulant Boiling Flow Visualization test loop has provided a unique opportunity to observe the processes occurring during two-phase, oscillatory flow with heat addition.

2. The SBFV has, in general, functioned as expected and has generated a significant amount of data, both qualitative (visual observation) and quantitative (instrument).

3. The processes controlling two-phase oscillatory flow are extremely complex and consist of interactions between the loop geometry (inertance, resistance, gravity) and fluid properties (density, two-phase friction, heat transfer).

4. Water behavior is similar in many respects to that of liquid sodium under two-phase conditions; data from the SBFV have proved helpful in interpreting data from SBT loop testing.

5. A one-dimensional boiling model using thermodynamic equilibrium conditions with slip between the phases has been used for analysis of the experimental data. Good agreement between the data and the analytical results has been obtained.

6. The use of high-speed motion pictures and the analytical modeling has improved understanding of low-power, low-flow boiling. The flow regimes and system stability characteristics have been experimentally identified in both forced and natural convection and have been studied analytically. This information will aid in the understanding and modeling of these phenomena in sodium systems.

Future experiments and improvements are planned for the SBFV loop. A series of tests is planned to investigate the effects of bypass ratio on system stability and oscillatory behavior. Also, a 7-pin SBFV test section has been designed. This test section is a hexagonal array of glass tubes with outside diameters of ~ 7 mm; this is prototypical of LMFBR driver fuel bundles. Glycerine will flow upward *inside* the glass tubes providing a heat source for water flowing through the array. The

test section is contained by a hexagonal glass duct wall, which is in turn surrounded by another glass duct. This configuration allows water at various temperatures to provide a series of different thermal boundary conditions for the bundle. The tubes will be spaced by wire-wraps, four of which will contain thermocouples similar to those used in the THORS facility LMFBR bundle tests in sodium. Although these wire-wraps will be metal, they are sufficiently small (~1.2-mm OD) to provide minimal interference during visual observation. This test section will be installed in place of the simple glass tube now in place. Other loop instrumentation will remain the same.

Computer modeling of simulant tests will also continue during the bypass ratio and multi-pin array tests.

Appendix A

SCALING PARAMETERS FOR COMPARISON OF WATER
AND SODIUM OSCILLATORY FLOWS

A major objective of SBFV testing has been to use the water data and observations to help interpret sodium boiling data from the SBT and THORS facilities. Emphasis has centered on SBT data because of the similarity in the SBT and SBFV loop geometry. In order to provide a rational basis for the use of water data to model sodium behavior, a set of scaling parameters based on loop geometry, test conditions, and fluid properties must be used. If these scaling parameters are matched, the behavior of one system should be able to provide a good simulation of the behavior of the others.

The scaling analysis used for the comparison of the SBT and SBFV data is based on a simplified model of loop behavior derived in Ref. 5. The actual equations describing fluid behavior (mass, momentum, and energy conservation) will not be derived here again; only the manipulation of these equations to provide scaling parameters is shown.

The simple model assumes that the system can be described as a vapor bubble in between two liquid columns. This configuration is shown in Fig. A.1. The bubble is allowed to expand and contract by means of evaporation or condensation and by means of compressibility effects within the vapor space.

The equation governing the motion of the two liquid columns is

$$I \frac{dQ}{dt} = \ell \frac{dP}{dz} - \ell \frac{d\tau}{dy} - \rho_f g \ell , \quad (A.1)$$

where I is the fluid inertance $\rho_f \ell / A$. Scaling parameters are derived by making the equation dimensionless by multiplying or dividing the variables by reference quantities. Thus, letting starred variables represent dimensionless variables (see Nomenclature for definitions of

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Fig. A.1. Bubble slug model used for derivation of system equations governing single-tube boiling oscillations.

variables):

$$\ell^* = \ell / L ,$$

$$A^* = A / D^2 ,$$

$$P^* = P / P_0 ,$$

$$\tau^* = \tau / \rho v_0^2 ,$$

$$y^* = y / D ,$$

$$z^* = z / L ,$$

$$Q^* = Q / Q_0 ,$$

$$t^* = t v .$$

(A.2)

Substituting in Eq. (A.1),

$$\frac{\rho L}{D_o^2} \frac{Q_o v}{P_o} \frac{1}{A^*} \frac{dQ^*}{dt^*} = \frac{dP^*}{dz^*} - \frac{\rho v_o^2 L}{DP_o} \frac{d\tau^*}{dy^*} - \frac{\rho_f g L}{P_o} . \quad (A.3)$$

The coefficient of the term on the left-hand side of Eq. (A.3) represents the scaled inertial pressure drop; it consists of the inertance (within a constant $4/\pi$) multiplied by a term representing the severity of the oscillation, as a ratio to the reference pressure. The coefficient of the dimensionless shear stress gradient term represents the frictional pressure drop; the ratio shown is normally denoted by a friction factor f , since by convention

$$\Delta P = \frac{fL}{D} \frac{\rho v^2}{2} , \quad (A.4)$$

and the coefficient therefore represents the reciprocal of f . The coefficient of the last term represents the scaled gravitational pressure drop. It is actually the interaction between the frictional and gravitational terms that determines the average (steady-state) behavior of the system in natural convection, since the difference in thermal centers between the bypass (cold) and test section (hot) legs drives the flow and the friction resists it. The inertial pressure drop is important only when the flow changes rapidly as a function of time, as in oscillatory flow. The inertance factor can therefore provide an indication of whether the character of the oscillations in two systems is similar; that is, whether the balance of the three terms is approximately the same.

The equation describing the behavior of the vapor space is

$$Q_g = \frac{dV_g}{dt} + \frac{V_g}{\rho_{g,sat}} \left(\frac{d\rho_{g,sat}}{dt} \right) . \quad (A.5)$$

However, the term dV_g/dt is simply the change in volume represented by the two liquid legs in Eq. (A.1). Therefore, the compressibility effect

Q_{com} is the second term on the right-hand side, or

$$Q_{com} = \frac{V_g}{\rho_{g,sat}} \frac{d\rho_{g,sat}}{dt} . \quad (A.6)$$

The equation is once again made dimensionless; to aid in this, the vapor space is represented as the vapor area αA times the boiling length L_g .

Then,

$$Q_c^* = Q_{com}/Q_o , \quad (A.7)$$

$$t^* = tv ,$$

and

$$Q_c^* = \frac{\alpha A L_g v}{Q_o} \frac{1}{\rho_{g,sat}} \frac{d\rho_{g,sat}}{dt^*} . \quad (A.8)$$

Dividing the coefficient by the inertance factor,

$$\frac{\alpha A L_g v}{Q_o} \bigg/ \frac{\rho_f L}{D^2} \frac{Q_o v}{P_o} = \frac{\alpha A D^2 P_o}{\rho_f Q_o^2} \frac{L_g}{L} . \quad (A.9)$$

The void fraction α is dimensionless, as is the term L_g/L , the dimensionless boiling length. The remaining term $A D^2 P_o / \rho_f Q_o^2$ can also be represented as $P_o / k \rho_f v_o^2$, since the volumetric flow Q_o is the product of the velocity and area. This once again has the form of a friction or form loss factor.

The final equation used is the one which determines the energy balance on the vapor space. This can be written as

$$Q_g = q_{vap} / \rho_{g,sat} h_{fg} . \quad (A.10)$$

The heat input to the bubble, q_{vap} , can also be written as the difference between the total heat input and that supplied to the liquid:

$$q_{vap} = q_T - q_{liq} . \quad (A.11)$$

The liquid heat input is simply the liquid mass flow times its change in

enthalpy:

$$q_{liq} = \dot{m}_f (h_{f,sat} - h_{in}) . \quad (A.12)$$

Thus,

$$Q_{vap} = \frac{q_T}{\rho_{g,sat} h_{fg}} - \frac{\dot{m}_f (h_{f,sat} - h_{in})}{\rho_{g,sat} h_{fg}} . \quad (A.13)$$

The product $\rho_g Q_g$ is the mass flow of vapor, $\dot{m}_g$. If this is divided by the liquid inlet flow $\dot{m}_{f,in}$, the ratio is the quality x . Then,

$$x = \frac{q_T}{\dot{m}_{f,in} h_{fg}} - \frac{(h_{f,sat} - h_{in})}{h_{fg}} . \quad (A.14)$$

Since q_T is the independently adjustable parameter, the outlet quality x and the subcooled inlet "quality," represented by $(h_{f,sat} - h_{in})/h_{fg}$, are two additional scaling parameters. If two of the three terms x , L_g/L , and $(h_{f,sat} - h_{in})/h_{fg}$ are identical for two systems, the third term will also be the same.

Returning to the dimensionless compressible flow shown in Eq. (A.9), it is seen that the void fraction appears as a dimensionless quantity, as previously noted. The definition of void fraction states that

$$\alpha = \frac{1}{1 + \frac{1-x}{x} \frac{\rho_{g,sat}}{\rho_{f,sat}} S} . \quad (A.15)$$

If, therefore, the void fraction is to be used as a scaling parameter, the product of the quality, slip ratio, and density ratio must be equal in two systems. The quality already appears in Eq. (A.13) as another scaling parameter. If liquid and vapor velocities are approximately equal, $S = 1$, then the density ratio $\rho_{g,sat}/\rho_{f,sat}$ appears as the final scaling factor.

Using these scaling parameters, the two loops can be compared to see if they behave in approximately the same manner. This comparison has been made for the modified SBFV loop configuration and the SBT loop.

The inlet and heated sections are treated as one leg, while the outlet (upper unheated zone) is treated as the second leg. The bypass is not considered for frictional and inertial factors since its diameter is much larger than that of the test section; the plena are also disregarded for this reason.

The geometry of the loops and the maintenance of plenum temperatures at values fixed by scaling considerations imply that the difference in thermal centers of the two loops is approximately equal. The flow is then generated by a balance of frictional (and, if applicable, inertial) forces against that of gravity. Since the friction factor appears as a scaling factor, it is essential to include its effect. However, the friction factor is usually represented as an empirically derived function of the Reynolds number, $\rho_f v D / \mu$. Dividing the frictional pressure drop term (fL/D) ($\rho_f v^2/2$) into its components, it is seen that the term $\rho_f L/D$ becomes important; this term agrees to within ~15% for the two loops. The velocity is what is to be determined. Therefore, it seems justifiable to express the friction factor by itself in terms of the Reynolds number. Thus,

$$v(\text{SBFV}) \cong v(\text{SBT}) \frac{\mu_{\text{SBFV}}}{\mu_{\text{SBT}}} \frac{\rho_{\text{SBT}}}{\rho_{\text{SBFV}}} \frac{D_{\text{SBT}}}{D_{\text{SBFV}}} . \quad (\text{A.16})$$

Substituting values for the fluid properties and test section diameter,

$$v(\text{SFBV}) \cong 1.15 v(\text{SBT}) . \quad (\text{A.17})$$

To determine the relationships between volumetric flows and oscillation frequencies, the velocity is multiplied by the test section area, so that

$$Q(\text{SBFV}) \cong 1.74 Q(\text{SBT}) . \quad (\text{A.18})$$

Since $Q \propto 1/v$,

$$v(\text{SBFV}) \cong 0.57 v(\text{SBT}) . \quad (\text{A.19})$$

These factors and several other scaling parameters are shown in Table A.1.

The major area of discrepancy between the two systems is in the density ratio. The higher value for the sodium system implies that it is a "stiffer" system and would tend to oscillate even slightly faster than shown in the previous analysis, with lower fluctuations in pressure. The "softer" water system would tend to have larger amplitude oscillations and larger swings in pressure. This is indeed what is seen in the sodium and water data presented in Sect. 6. However, the comparison of the data indicates that the flows and oscillation frequencies are very close to what the scaling analysis predicts; this suggests strongly that the behavior of the two systems is driven by the same mechanisms and that the SBFV data can be used to model the oscillatory behavior of the SBT loop.

Table A.1. Scaling parameters for SBT and SBFV loops

	SBT	SBFV (with coil)
Inertance factor		
Inlet + heated sections	$2.9 \times 10^3 Q_0 v$	$3.2 \times 10^3 Q_0 v$
Outlet sections	$1.1 \times 10^3 Q_0 v$	$0.96 \times 10^3 Q_0 v$
Friction pressure drop term, $\rho_f L/D$, kg/m^3		
Inlet + heated sections	1.1×10^6	1.3×10^6
Outlet section	3.7×10^5	3.9×10^5
Velocity scaled by Reynolds No., m/s	1.0 (reference)	1.15
Frequency scaled by inertance factor, Hz	1.0 (reference)	0.57
Liquid saturation density at atmospheric pressure, kg/m^3	740	958
Vapor saturation density at atmospheric pressure, kg/m^3	0.274	0.598
Density ratio, $\rho_{f,sat}/\rho_{g,sat}$	2700	1600

Appendix B

ERRORS AND UNCERTAINTIES IN SBT AND SBFV EXPERIMENTAL DATA

During experimentation in both the SBT and SBFV loops, all efforts were made to ensure that precision and accuracy of instrument data were maintained at high levels. Nevertheless, uncertainties and errors in the data from both of these loops have been identified, particularly with respect to flow and power in the test section. In the SBFV tests, problems associated with the test section turbine flowmeters have been outlined in Sect. 5. These will also be explored further, as well as uncertainties in other measured and derived parameters. Some of the errors associated with the SBT facility have been previously discussed in Ref. 2. That discussion will be reviewed briefly, and additional information regarding this loop will also be examined.

The pressure and temperature instrumentation in the SBFV loop functioned extremely well. The pressure transducer data agree, in general, with readings from the Bourdon tube gage mounted on the loop. Even when overranged by as much as 100% of full scale, the transducers continued to operate accurately and reliably. The vendor's specifications claim an accuracy of $\pm 1.0\%$; based on the performance of these instruments, there appears to be no reason to question the given figure. The thermocouples in the SBFV loop also functioned, in general, very well. There were isolated instances of thermocouples giving erroneous readings, but all of these problems were traced to faulty connections rather than to inherent problems with the instruments themselves. The upper end of the temperature range for Chromel-Alumel thermocouples is over 1000°C ; it would not be expected that temperature-induced difficulties would be noticeable. In several tests, however, the thermocouples did not read the actual water temperatures, as desired, but registered instead some intermediate temperature between those of the water and glycerine. In the case of Test 100 Run 113, this can be attributed to the degradation of heat transfer at the thermocouple bead caused by dryout and a subsequent temperature rise. In the Test 400 runs presented, these high readings can be attributed to the fact that the bead of the thermocouple

did not project far enough into the fluid to preclude interference from the test section wall; the instrument was therefore probably reading a temperature very close to the wall temperature. Aside from these variations, the test section thermocouples performed well, and their readings during boiling agreed quite closely with the saturation temperatures corresponding to pressure data, providing further confirmation of the accuracy of both instrument types. The RTDs, used to measure glycerine temperatures, also performed very reliably. The precision of these instruments, as measured by the amount of fluctuation in steady state, was extremely high, and proper calibration ensured high accuracy as well.

The flow instrumentation in the SBFV loop, as noted previously, provided the largest uncertainties. These uncertainties also carried over to affect estimates of test section power. All of the flowmeters used in the SBFV loop were turbine type; the principle of operation is that the flow of fluid causes the turbine to spin. The rate of spin of the meter is dependent upon the density, velocity, and viscosity of the fluid, and the meter must be calibrated for different fluids. The rotation of the turbine is sensed by pickups on the body of the meter, which convert the pulses to an analog or digital signal. The glycerine and bypass flowmeters are both unidirectional, in that they have only two pickups and cannot discriminate the direction in which the fluid is flowing. Both of these flowmeters performed quite well, although contamination in the glycerine flowmeter occasionally caused it to stick. The bypass flowmeter was subjected to flows in both positive (upward) and negative (downward) directions. While the positive readings are considered to be accurate within the resolution capability of the instruments, the negative flows (which also produce positive signals, as noted above) cannot be regarded as quantitatively accurate.

The test section flowmeters are bidirectional, in that they have additional pickups to allow discrimination of the flow direction. Therefore, a positive (upward) flow produces a positive signal and a negative (downward) flow produces a negative signal. The instruments in the SBFV were calibrated in both directions, but only for single-phase water.

During two-phase flow, the outlet flowmeter was subjected to both steam-water and pure steam flow. Flowmeter readings during these periods cannot be regarded as accurate, and they serve mainly to indicate the direction of flow. The passage of steam through the meter caused the turbine to spin at a rate too high for the gain level set on the DAS, producing a "flat-top" signal. This behavior has also been previously discussed. The inlet flowmeter was subjected to very little two-phase flow and, in fact, operated fairly reliably. It did have a tendency to stall at a very low flow because of the inertia of the turbine; data from several tests show zero readings in oscillatory flow. However, the readings on the flowmeter correspond well to rates of flow observed visually; and the oscillatory behavior of the flow agrees qualitatively (frequency, severity, etc.) with the behavior observed in the pressure and temperature data.

One uncertainty in inlet flow has, as yet, not been resolved. Visual observation (directly and in motion pictures) shows liquid slugs streaming upward during periods of two-phase oscillations while the flowmeter indicates negative flow. Because of the large density ratio of liquid water to steam ($\rho_f/\rho_g \sim 1600$ at atmospheric pressure), a very large volumetric vapor flow contains the same mass as a very small volumetric liquid flow. Therefore, a vapor core pushing down through the inlet flowmeter could be counteracted by the upward flow of a liquid film on the test section wall that would not necessarily register in the flowmeter. A similar type of behavior could occur even in single-phase flow, if a core of liquid were to push down against a liquid column in the center of the flowmeter, causing a recirculating upward flow at the wall of the meter. Readings of the flow during this type of behavior could be erratic, sometimes positive, sometimes negative, and might account for some of the reverse flows registered during forced convection tests, such as in Test 103 Run 101. Further tests in the SBFV loop will be required to resolve this issue.

Since the test section power was derived by a heat balance in the glycerine, the flow and temperature measurements in the glycerine system are crucial to the determination of this parameter. Additionally, the

glycerine flow was kept at a relatively high value to improve heat transfer ($\sim 0.20\text{--}0.25$ L/s) so that the temperature differences between inlet and outlet were small, and small fluctuations caused significant changes in power. In addition, losses to the environment, via natural convection to the air, and radiation heat transfer are not considered. Because of the low temperature of the glycerine (relatively speaking), the combination of these effects is estimated to cause about a 10% loss in the test section power. A calculation is shown at the end of the appendix to illustrate the contributions from convection and radiation. Of importance, too, are temperature and flow fluctuations. Small variations in both of these parameters were seen throughout all of the tests. With the exception of Test 100 Run 113 and Test 21 Run 2, in which internal test section conditions dramatically affected the power transferred to the test section, all of the average powers reported for the SBFV tests are considered to be accurate within $\sim 10\text{--}15\%$.

Although the reported powers are considered to be fairly accurate, it should be stressed that the axial power profile is clearly not uniform. The temperature-controlled system is dependent on the heat transfer coefficients of the two fluids plus the resistance of the glass tube wall for the transfer of heat from the glycerine to the water. In boiling particularly, the heat transfer coefficient on the water side is not uniform axially and may vary by as much as an order of magnitude between the single-phase flow at the inlet and the boiling flow at the outlet. Additionally, the temperature difference between the fluids is constantly changing, so that the power is affected by that parameter. These effects combine, in all likelihood, to skew the power profile toward the top of the heated zone, which is just the opposite of the behavior of the SBT, as will be shown. The differences between the calculated behavior of temperature- and power-controlled systems are discussed in Appendix C.

Data from the SBT facility tests included readings from pressure, flow, temperature, void, and power instrumentation; only pressure and flow data are compared for tests at scaled equivalent powers using the nominal powers reported for both loops. Temperature data are not used for reasons discussed previously; void instrumentation does not exist in

the SBFV, and visual observation does not provide sufficient resolution to compare instrument void data to visually observed boiling patterns.

The permanent magnet flowmeters used in the SBT facility were originally designed for higher flows than the 0–10 mL/s range observed. The flowmeters were calibrated in place in the loop, using forced convection flow. Nonetheless, the high temperature operation of the loops was very hard on instrumentation and could possibly cause instrument drift and other types of errors. The overall accuracy of the flow in the SBT tests is estimated in Ref. 2 to be approximately $\pm 15\%$. It should be noted, however, that pressure and flow fluctuations and oscillatory behavior agree qualitatively, and within the cited error band, the flowmeter is considered to be reasonably accurate.

Power measurements in the SBT loop were more problematical and subject to greater uncertainty. The SBT test section was indirectly heated using a quadelliptic radiant furnace. The "unheated" riser was actually heated by a clamshell guard heater to minimize heat losses to the environment. The power to the sodium was calculated by adding the power to the furnace and clamshell heaters and then subtracting the estimated losses to the environment and the power removed by the water cooling the furnace. This calculation was subject to a number of uncertainties — the measurement of furnace and clamshell powers, estimation of losses, and coolant heat rejection (calculated by a heat balance on the water, whose flow was measured with a turbine flowmeter). In addition, full power was delivered to the test section only when the tube stayed in the focus of the furnace. Although the inlet coil was designed to accommodate thermal expansion and thereby keep the tube from bending, there is considerable evidence that warping did indeed occur. Figure B.1 shows an axial temperature profile for SBT Test 129R1. Clearly, the power profile is skewed toward the bottom of the test section, as one would expect for a warped test section, since warpage is most likely in the highest temperature region. Studies done by Garrison² and by Huh¹¹ at MIT show that SBT powers may have been overestimated by as much as 30%. The skewing of the power profile — toward the bottom in the SBT loop and toward the top in the SBFV tests — and the uncertainties in

Fig. B.1. Test section axial temperature profile for SBT test 129R1.

test section power may well explain many of the differences in the behavior of the two experiments.

Calculation of Heat Losses

The loss of heat from the test section results from natural convection losses to the air and radiation heat transfer from the exterior surface of the glass. An order of magnitude estimate for the natural convection heat transfer coefficient is $\sim 10 \text{ W/m}^2 \cdot ^\circ\text{C}$. For one of the SBFV tests at a power of 1.6 kW, the glycerine temperature was $\sim 175^\circ\text{C}$. The low convective coefficient at the glass surface means that the glass surface temperature is about 170°C . Thus, the radiation heat loss (assuming gray body radiation, a Pyrex emissivity of ~ 0.90 , a view factor of 1.0, and an air temperature of 25°C) is

$$q_{\text{rad}} = A \epsilon \sigma (T_{\text{Pyrex}}^4 - T_{\text{air}}^4) = \pi (0.015 \text{ m}) (0.965 \text{ m}) (0.90) \\ \times (5.673 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4) [(443 \text{ K})^4 - (298 \text{ K})^4] = 71.12 \text{ W} .$$

Additionally, the convective heat transfer is

$$q_{\text{conv}} = h A (T_{\text{Pyrex}} - T_{\text{air}}) = (10.0 \text{ W/m}^2 \cdot ^\circ\text{C}) (\pi) (0.015 \text{ m}) \\ \times (0.965 \text{ m}) (170^\circ\text{C} - 25^\circ\text{C}) = 65.93 \text{ W} .$$

The total heat loss q_T is thus ~ 137.05 W. In the riser section, assume the surface temperature is 95°C , then

$$q_{\text{rad}} = (\pi)(0.0060 \text{ m})(1.575 \text{ m})(0.90)(5.673 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4) \\ \times [(368 \text{ K})^4 - (298 \text{ K})^4] = 15.85 \text{ W} ,$$

$$q_{\text{conv}} = (10 \text{ W/m}^2 \cdot ^\circ\text{C})(\pi)(0.0060 \text{ m})(1.575 \text{ m})(95^\circ\text{C} - 25^\circ\text{C}) = 20.78 \text{ W} ,$$

$$q_T = 36.63 \text{ W} ,$$

$$q_{T,\text{heated}} + q_{T,\text{riser}} = 173.68 \text{ W or } \sim 11\% \text{ of } 1.6 \text{ kW} .$$

Note that the radiative loss is approximately equal in magnitude to the convective loss at this temperature; at lower temperatures, characteristic of lower power runs, this contribution will drop faster than the convective loss because of its fourth-power dependence. In addition, the convective heat transfer coefficient is dependent on the surface temperature, since a higher temperature creates more buoyancy and higher flow near the surface. For tests near 1.3–1.4 kW, the losses are estimated to drop below 10%.

The calculation of heat losses is subject to uncertainties because of the assumptions made in the determination of the radiative and convective coefficients. However, it is probably within 20% of the actual losses.

Appendix C

A COMPARATIVE STUDY OF WATER BOILING IN A VERTICAL
TUBE UNDER TEMPERATURE-CONTROLLED OR HEAT-FLUX-
CONTROLLED BOUNDARY CONDITIONS

The testing performed in the SBFV loop differed from most other experiments of this nature, in that a hot fluid was used to heat the working fluid. As a result of this design, the behavior of the system was governed by a temperature-controlled boundary condition rather than the power-controlled boundary condition present in directly heated test loops. In order to compare the SBFV data with previous experiments using a stainless steel test section and a power-controlled boundary condition, a comparative study of the effect on water boiling with the two different boundary conditions was performed. The computer program LOOP-W was modified so that analogous cases could be run with the two different boundary conditions.

The program as set up for a temperature-controlled boundary condition was described previously in Sect. 7. For the case of a power-controlled boundary condition, the heat conduction equation in cylindrical coordinates solved is

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} r k \frac{\partial T}{\partial r} + \frac{S}{V_s}, \quad (C.1)$$

where S/V_s is the volumetric source, assumed to be uniformly distributed in the heated part of the test section. An adiabatic boundary condition is assumed at the external wall. The same equation used in Sect. 7 is used here to calculate the total power input into the water:

$$q_{in} = \sum_{j=1}^n h_{in}^j A_{in} (T_{in}^j - T_w^j). \quad (C.2)$$

The same heat transfer coefficients as used in the case of the temperature-controlled boundary condition cases are used here. Equation (C.1) is solved using finite differences in the radial direction (ten nodes) and neglecting axial conduction.

Test 300 Run 105, a natural convection run, was chosen as the reference case, and calculated values using the temperature-controlled boundary conditions were presented in Sect. 7. The calculated power for this run was 1.1 kW.

Another calculation was performed using the power-controlled boundary condition, glass properties, and a constant value of the power at 1.1 kW. Figure C.1 shows the results, and comparing them with Fig. 7.10, no significant differences are observed. The period obtained was 6.2 s, comparable to the 6.1-s period obtained in the calculation with the temperature-controlled boundary condition of Fig. 7.10. The only noticeable difference is that the amplitude of the oscillations calculated for the pressure at PE-10 and for the outlet flow are larger in Fig. C.1 than in Fig. 7.10. The power into the water was also calculated in this last case by Eq. (C.1) and is given in Fig. C.2. It can be seen that although the power into the structure is constant, at a value of 1.1 kW, the power into the water is not constant, and it displays oscillations similar to those in the case of temperature-controlled boundary condition. The average value of the power of Fig. C.2 was also 1.1 kW. Figure C.3 shows heat transfer coefficients calculated at the same position as in Fig. 7.14 (third node of the heated section), and it can be seen that they are considerably larger than those of Fig. 7.14. This may partially explain the fact that the amplitude of the oscillations is also larger in the case of the power-controlled boundary condition.

Additional calculations were performed varying the value of the input power. Different oscillatory periods were obtained. For a lower power of 1.0 kW, the calculated period was 7.3 s (Figs. C.4 and C.5); for a power of 1.5 kW, the obtained period was 4.7 s (Figs. C.6 and C.7). That is, the higher the power, the shorter the period of the oscillations. These results follow the same trends as previously calculated and measured values.

Stainless steel properties were used for the structure in the next run, with a constant input power boundary condition using finite differences in the solution of the heat conduction equation [Eq. (C.1)] and an input power of 1.1 kW. The results are given in Figs. C.8 and C.9. The

Fig. C.1. LOOP-W calculated results for the glass test section with constant input power (1.1 kW).

Fig. C.2. LOOP-W calculated power into the water for the 1.1-kW glass test section run (power-controlled boundary condition).

Fig. C.3. LOOP-W calculated heat transfer coefficients for the 1.1-kW glass test section run (power-controlled boundary condition).

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Fig. C.4. LOOP-W calculated results for the glass test section with constant input power (1.0 kW).

Fig. C.5. LOOP-W calculated input power for the 1.0-kW glass test section run (power-controlled boundary condition).

oscillations calculated with the stainless steel test section are irregular and their amplitude is smaller. The average oscillatory period obtained is 7.4 s, ranging from 5.9 s to 9.4 s. If the specific heat of the structural material used in these calculations is varied, different periods and amplitudes of the oscillations are obtained. This emphasizes the importance of the thermal properties of test section material on the boiling behavior. These runs are summarized in Table C.1.

These calculations suggest that there is little difference on the boiling process performed through either a temperature-controlled or a power-controlled boundary condition. Therefore, the SBFV loop can adequately simulate a power-controlled experimental facility. However, the effect of the thermal properties of the structural material is very important to the period and the amplitude of the boiling oscillations and therefore should be taken into consideration when comparing data obtained in test sections of different materials.

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Fig. C.6. LOOP-W calculated results for the glass test section with constant input power (1.5 kW).

Fig. C.7. LOOP-W calculated input power for the 1.5-kW glass test section run (power-controlled boundary condition).

Table C.1. Comparison of results between experimental (temperature-controlled) and calculated (both temperature- and power-controlled boundary conditions)

Case	Material	Figure No.	Boundary condition	Power (kW)	τ (s)
Test 300 Run 105 (experiment)	Glass	7.11	$T_{gl} = 170^{\circ}\text{C}$	1.3	6.1
Calculated, with LOOP-W	Glass	7.10 and 7.12-1.14	$T_{gl} = 170^{\circ}\text{C}$	1.1	6.1
Calculated, with LOOP-W	Glass	C.1-C.3	Power	1.1	6.2
Calculated, with LOOP-W	Glass	C.4, C.5	Power	1.0	7.3
Calculated, with LOOP-W	Glass	C.6, C.7	Power	1.5	4.7
Calculated, with LOOP-W	Steel	C.8, C.9	Power	1.1	7.9

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Fig. C.8. LOOP-W calculated results for the stainless steel test section with constant input power (1.1 kW).

Fig. C.9. LOOP-W calculated power for the 1.1-kW stainless steel test section (power-controlled boundary condition).

Appendix D

TABLE OF SBFV TESTS

Table D.1 lists all tests that were done in the SBFV loop. The preliminary tests performed mainly for shakedown purposes were not numbered in any particular order; this is the reason for the proliferation of runs called "Test 1." The "Test 2" series runs included natural circulation and flow coastdown tests. The tests beginning with Tests 100 and 200 were natural forced convection tests that attempted to simulate SBT tests before the coil was installed.

After the decision was made to install the coil but before its installation, the 300 series of tests was run to produce data that could be compared with the new configuration. The 400 and 500 series were then run to produce data with the coil in place for comparison with both SBT and previous SBFV runs.

All tests indicated as a "natural circulation through bypass" had the pump leg valve closed; when the pump leg was open during natural circulation tests, the bypass valve was normally shut.

The powers chosen for the runs in Tests 101, 103, 107, and 200 were picked to correspond to scaled powers derived from SBT tests. The powers in Tests 300 and 400 were also chosen from these scaled powers; in addition, runs were made to determine the onset of boiling, the onset of oscillations, and the highest power possible to the water tube. The runs in Test 500 were performed to see if the data in Test 400 were reproducible. Therefore, the power (which could not be measured because of a failed glycerine flowmeter) was not particularly important; only the qualitative comparison of data was desired.

Table D.1. SBFV tests

Test No.	Run No.	Date	Length of test (s)	Approximate average power (kW)	Short description
1	1	10/16/81	180	1.24	Shakedown test — low-flow forced convection with bypass open
2	2	10/16/81	300	1.24	Shakedown test — low-flow forced convection with bypass open
3	3	10/16/81	60	1.51	Shakedown test — low-flow forced convection with bypass open
1	1	10/22/81	60	1.16	Shakedown test — natural circulation through bypass
1	2	10/22/81	60	1.17	Shakedown test — natural circulation through bypass
1	3	10/22/81	60	1.31	Shakedown test — natural circulation through bypass
1	1	10/27/81	60	1.25	Shakedown test — natural circulation through bypass
1	2	10/27/81	60	1.37	Shakedown test — natural circulation through bypass
1	3	10/27/81	60	1.43	Shakedown test — natural circulation through bypass
1	4	10/27/81	60	1.10	Shakedown test — natural circulation through bypass
1	1	11/3/81	120	0.74	Preliminary flow coast-down test at high power
1	2	11/3/81	120	0.26	Preliminary flow coast-down test at low power
1	1	11/9/81	180	1.26	Shakedown for inlet flowmeter — natural circulation through bypass
21	1	11/12/81	60	1.29	Natural circulation inlet through bypass
21	2	11/12/81	120	0.31	Flow coastdown test
102	100	2/17/82	60	1.51	Forced convection test with bypass open

Table D.1 (continued)

Test No.	Run No.	Date	Length of test (s)	Approximate average power (kW)	Short description
102	101	2/17/82	30	1.55	Forced convection test with bypass open
102	102	2/17/82	30	1.56	Forced convection test with bypass open
102	103	2/17/82	30	1.60	Forced convection test with bypass open
102	104	2/17/82	30	1.57	Forced convection test with bypass open
102	105	2/17/82	30	1.50	Forced convection test with bypass open
102	106	2/17/82	30	1.48	Forced convection test with bypass open
102	107	2/17/82	30	1.45	Forced convection test with bypass open
102	108	2/17/82	30	1.40	Natural circulation through bypass
102	109	2/17/82	30	1.39	Natural circulation through bypass
102	110	2/17/82	30	1.30	Natural circulation through bypass
102	111	2/17/82	30	1.43	Natural circulation through bypass
100	101	2/19/82	30	1.38	Natural circulation through bypass; valve open completely
100	102	2/19/82	30	1.38	Natural circulation through bypass; valve closed 3 turns
100	103	2/19/82	30	1.39	Natural circulation through bypass; valve closed 5 turns
100	104	2/19/82	30	1.39	Natural circulation through bypass; valve closed 6 turns
100	105	2/19/82	60	1.37	Natural circulation through bypass; valve closed 6.5 turns
100	106	2/19/82	60	1.33	Natural circulation through bypass; valve closed 7 turns
100	107	2/19/82	60	1.21	Natural circulation through bypass; valve closed 7.13 turns

Table D.1 (continued)

Test No.	Run No.	Date	Length of test (s)	Approximate average power (kW)	Short description
100	108	2/19/82	60	1.36	Natural circulation through bypass; valve closed 7.25 turns
100	109	2/19/82	60	1.36	Natural circulation through bypass; valve closed 7.33 turns
100	110	2/19/82	60	1.28	Natural circulation through bypass; valve closed 7.58 turns
100	111	2/19/82	60	1.23	Natural circulation through bypass; valve closed 7.66 turns
100	112	2/19/82	60	1.32	Natural circulation through bypass; valve closed ~7.75 turns
100	113	2/19/82	60	1.02	"No-flow" test — bypass valve closed
101	101F1	2/23/82	60	1.05	Forced convection, bypass slightly open
101	101F2	2/23/82	30	1.04	Forced convection, bypass slightly open
101	101F3	2/23/82	30	1.13	Forced convection, bypass slightly open
101	101F4	2/23/82	30	1.05	Forced convection, bypass slightly open
101	101F5	2/23/82	30	1.03	Forced convection, bypass slightly open
101	101F6	2/23/82	30	1.20	Forced convection, bypass slightly open
101	101F7	2/23/82	30	1.10	Forced convection, bypass slightly open
101	101F8	2/23/82	30	1.00	Natural circulation, bypass slightly open
101	101F9	2/23/82	30	1.10	Natural circulation, bypass slightly open
101	101F10	2/23/82	30	1.10	Natural circulation, bypass slightly open
101	101F11	2/23/82	30	1.04	Natural circulation, bypass slightly open
202	101F1	2/25/82	60	1.29	Forced convection, bypass slightly open
202	101F2	2/25/82	30	1.32	Forced convection, bypass slightly open

Table D.1 (continued)

Test No.	Run No.	Date	Length of test (s)	Approximate average power (kW)	Short description
202	101F3	2/25/82	30	1.39	Forced convection, bypass closed
202	101F4	2/25/82	30	1.45	Forced convection, bypass closed
202	101F5	2/25/82	30	1.37	Forced convection, bypass closed
202	101F6	2/25/82	30	1.33	Forced convection, bypass closed
202	101F7	2/25/82	30	1.37	Forced convection, bypass closed
202	101F8	2/25/82	30	1.44	Forced convection, bypass closed
202	101F9	2/25/82	30	1.27	Natural circulation through pump leg
202	101F10	2/25/82	30	1.38	Natural circulation through pump leg
202	101F11	2/25/82	30	1.33	Natural circulation through pump leg
202	101F12	2/25/82	180	1.39	Natural circulation through pump leg
103	101F1	3/1/82	60	1.44	Forced convection, bypass closed
103	101F2	3/1/82	30	1.43	Forced convection, bypass closed
103	101F3	3/1/82	30	1.49	Forced convection, bypass closed
103	101F4	3/1/82	30	1.55	Forced convection, bypass closed
103	101F5	3/1/82	30	1.61	Forced convection, bypass closed
103	101F6	3/1/82	30	1.51	Forced convection, bypass closed
107	101F1	3/4/82	60	1.44	Forced convection, bypass closed
107	101F2	3/4/82	30	1.46	Forced convection, bypass closed
107	101F3	3/4/82	30	1.45	Forced convection, bypass closed
107	101F4	3/4/82	30	1.54	Forced convection, bypass closed
107	101F5	3/4/82	30	1.54	Forced convection, bypass closed
107	101F6	3/4/82	30	1.55	Forced convection, bypass closed

Table D.1 (continued)

Test No.	Run No.	Date	Length of test (s)	Approximate average power (kW)	Short description
107	101F7	3/4/82	30	~1.15	Forced convection, bypass closed
107	101F8	3/4/82	30	~1.6 ^a	Forced convection, bypass closed
107	101F9	3/4/82	60	~1.6 ^a	Forced convection, bypass closed
300	105	3/9/82	180	1.31	Natural circulation through bypass
300	106	3/9/82	180	1.37	Natural circulation through bypass
300	107	3/9/82	180	1.45	Natural circulation through bypass
300	108	3/9/82	180	1.63	Natural circulation through bypass
300	1011	4/1/82	180	0.80	Natural circulation through bypass
300	1021	4/1/82	180	1.16	Natural circulation through bypass
300	1012	5/11/82	180	0.52	Natural circulation through bypass
300	1022	5/11/82	180	0.66	Natural circulation through bypass
300	1032	5/11/82	180	1.90	Natural circulation through bypass
300	1042	5/11/82	180	2.20	Natural circulation through bypass
300	1052	5/11/82	180	2.46	Natural circulation through bypass
<u>Inlet coil installed</u>					
400	101	5/18/82	180	1.11	Natural circulation through bypass
400	102	5/18/82	180	1.38	Natural circulation through bypass
400	103	5/21/82	60	0.26	Natural circulation through bypass
400	104	5/21/82	120	0.59	Natural circulation through bypass
400	105	5/21/82	120	0.89	Natural circulation through bypass
400	106	5/21/82	180	1.56	Natural circulation through bypass
400	107	5/21/82	180	1.74	Natural circulation through bypass

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Table D.1 (continued)

Test No.	Run No.	Date	Length of test (s)	Approximate average power (kW)	Short description
500	101	7/20/82	60	<i>b</i>	Natural circulation through bypass
500	102	7/20/82	60	<i>b</i>	Natural circulation through bypass
500	103	7/20/82	120	<i>b</i>	Natural circulation through bypass

^aGlycerine flowmeter failed.

^bGlycerine flowmeter did not function during Test 500; power approximated from glycerine temperatures and pump setting at ~1.2–1.4 kW.

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ABSTRACT: Experiments have been performed in a transparent, single-tube boiling loop, using water as the working fluid, to simulate sodium boiling behavior in a similar geometry. Testing has been performed over a wide range of flows, powers, and temperatures to examine the onset of boiling, flow regimes, oscillatory flow behavior, and dryout. Analysis of experimental data has been aided by the use of high-speed motion pictures. Instrument data from selected tests are presented and discussed, as well as results from computer simulations of the experiments. The computer model is presented, and scaling laws for the comparison of water and sodium oscillatory boiling are discussed. Comparison of the data from this loop with sodium boiling data has shown that an atmospheric pressure, two-phase water system is a good simulant for boiling liquid sodium. 11 refs., 91 figs., 2 tabs.