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This qualification effort was part of a larger effort undertaken by the Lcs Alamos National Laboratory for the US Department of Energy to independently confirm power limits for the Savannah River Site K Reactor. The results of this benchmark effort as discussed in this paper demonstrate that TRAC-PF1/MOD3 coupled with proper modeling is capable of simulating thermal-hydraulic phenomena typical of that encountered in a Mark-22 fuel assembly during LOCA/ECS conditions.

INTRODUCTION

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As part of its mission to establish safe operating power limits for the K Reactor, SRL performed a number of single-annulus heated experiments to better understand two-phase heat transfer and hydraulics in air-water downflow in narrow ribbed annuli. The experimental geometry was typical of that encountered in a single annulus of the Mark-22 fuel assembly. The SRL experiments (Rig FA,[2-15] Rig FB,[18] Rig B,[19] etc.) provided data to establish criteria for setting assembly ECS power limits and data for benchmarking the FLOWTRAN-TF code.[20,21] A conservative ECS power limits criterion, termed $T_{wall} = T_{sat}$,[22] was adopted by SRL to ensure that no point on the fuel assembly wall would exceed the local saturation temperature. To support the basis for this limit, considerable testing was performed by SRL using Rig FA.[7,9,15]

The Rig FA test section consists of an electrically heated 149.5-in.-long, 3.309-in.-o.d. instrumented ribbed aluminum annulus with a 0.308-in. gap. A flame-sprayed heater on the outside of the annulus provided the heat source for the test rig, and adiabatic heatup tests characterized the axial and azimuthal heater profiles. Both single- and two-phase downflow tests were performed by establishing pressure boundary conditions and setting the liquid flow rates into the test annulus. For two-phase air and water tests, air was entrained as necessary to match the established boundary conditions. For limits testing, power to the heaters was increased in small increments, allowing steady-state conditions to be established until the annulus wall temperatures reached a predetermined value. The range of test conditions, i.e., water flow and assembly pressure differences, was designed to be typical of those encountered by a Mark-22 fuel assembly during the ECS phase of a LOCA.

A two-dimensional (theta, z) representation of the Rig FA test annulus was developed using the TRAC vessel component. This model, which provided the basis for later modelling of the Mark-22 fuel assembly, was used to benchmark the complete spectrum of Rig FA tests. Code calculations were performed for the single-phase pressure drop tests, two-phase unheated tests, adiabatic heatup tests, single- and two-phase heated tests, heated air entrainment tests, and $T_{wall} = T_{sat}$ power limits tests.

Preliminary calculations indicated a need to make certain modifications to the TRAC constitutive models to better simulate the effect of a noncondensible gas (i.e., air) on heat transfer and hydraulics for narrow ribbed annuli. As a result, new wall heat-transfer, wall shear, and interfacial shear models[23] were introduced into TRAC-PF1/MOD3 to improve the two-phase modeling of the Mark-22 fuel assembly.

This paper discusses (a) the test facility, test procedure, qualification tests, and $T_{wall} = T_{sat}$ limits tests; (b) the development of the TRAC model; (c) TRAC code modifications; and (d) TRAC calculations of qualification and limits tests.

RIG FA TEST FACILITY DESCRIPTION

A schematic of the major components of the Rig FA Test Facility is presented in Fig. 1. Rig FA was constructed by and tests were performed at the Westinghouse Savannah River Laboratory Heat Transfer Laboratory. J. L. Steimke was the principal investigator and has provided most of the relevant documentation. Rig FA originally was constructed to simulate one annulus of a Mark-22 fuel assembly under thermal-hydraulic conditions thought to be typical of the ECS phase of a LOCA. Testing was performed to determine the heat transfer and fluid flow mechanisms leading to thermal excursion. After the initial testing of Rig FA, SRL adopted the more restrictive $T_{wall} = T_{sat}$ power limit for Mark-22 LOCA/ECS limits, and thus, additional testing was performed using Rig FA.

The overall test loop consists of a pressure regulator vessel with an air supply to provide metered air at fixed pressure to the random inlet. Metered, deionized water passes through heat exchangers to establish desired temperatures and then is supplied to the random inlet. Liquid entering the random inlet entrains air, mixes thoroughly, and proceeds down into the test section. At the exit of the random inlet, just above the heated test section, are four bypass lines through which air and water mixtures can flow under certain test conditions (i.e., flooding or thermal excursion). The bypass tubes were used to simulate the other annuli present in a Mark-22 fuel assembly. Under test conditions up to $T_{wall} = T_{sat}$ power levels, no water was observed to flow through these bypass lines.

The 4.521-m-long test section consists of a narrow ribbed vertical annulus (i.d. = 0.0683 m, o.d. = 0.0761 m) as shown in Fig. 1. Rig FA has a diametral rib gap of 7.62e-04 m. At the exit of the test section, the air-water mixture enters four air-water separator tubes before it is recycled. Four liquid standpipes located at the exit of the test section provide a known back-pressure.

The random inlet, which is an experimental artifice to simulate the entrance region above the fuel assemblies in the K Reactor, is about 1.7 m long and provides good mixing of air and water. A "center body" is present in the random inlet to force the air-water mixture toward the exterior walls, thus creating the sort of chaotic flow pattern expected to be encountered at the entrance to a fuel assembly under ECS conditions.

The external heater for Rig FA was made almost entirely from aluminum—similar to the fuel tubes of the reactor fuel assemblies. The heaters were fabricated using a flame-spray technology to provide direct resistance heating. The heater consists of a 1.27e-04 m nickel-bond coat flame-sprayed onto the outside of an aluminum tube. A 3.81e-04 m layer of mixed aluminum oxide and titanium oxide followed. Finally, a 1.52e-04 m layer of aluminum was applied to provide a layer through which electric current could be passed to generate heat. The flame-spray process produced a heater that was almost entirely aluminum; however, because of the apparent porosity of the flame-spray-layer, thermal characterization of the heater proved to be difficult.

Thermocouples were mounted on the exterior of the heater and in the middle of each subchannel annulus as shown in Fig. 1. The thermocouples were spaced in the middle of each 90° azimuthal sector and axially at 0.3048-m intervals along the test section. In addition, more thermocouples are mounted at 15° increments on the outside of the heater in Subchannel A at 1.89 m and 3.109 m from the test section entrance. Ten pressure taps were provided to measure the axial pressure gradient from the random inlet through the test section. A rotameter and an airflow meter were used to monitor the liquid and air flows, respectively. Heated single-phase flow tests were used to calibrate the flame-spray heaters thermally.

A Macintosh-based data acquisition system was used to scan temperatures and flows once per second and to scan power about 15 times per second. Pressures and temperatures were calibrated at regular intervals, and testing began by first establishing the desired liquid flow rate. Inlet and outlet pressures then were adjusted to the desired conditions. For two-phase tests, the airflow was adjusted to the established pressure boundary conditions. For heated tests, 10 min at a given set of conditions was allotted to ensure steady-state conditions were achieved. For the $T_{wall} = T_{sat}$ tests, heater power was increased in increments until the limit criterion was approximately achieved, and then the data were logged. Data were taken at several powers to bound the actual limit. Data then were logged three times for 5 min each at a scan rate of once per 5 s.

Before the limits tests were performed, a number of "qualification" tests were carried out. These tests included (a) adiabatic heatup tests, (b) one- and two-phase unheated tests, and (c) one- and two-phase heated tests. These tests provided essential benchmarks for use in qualifying our TRAC model and are discussed in the Summary of TRAC Results section of this paper.

The range of test conditions, that is, assembly inlet and outlet pressures and liquid flows and temperatures, were chosen to bound the range of assembly conditions expected to occur during the ECS phase of a LOCA in the K Reactor. These conditions were estimated by SRL to be as follows: liquid flows between 4 and 16 gal./min, inlet liquid temperatures from 30°C to 60°C, and assembly pressure differences of 0.0 m. to -1.89 m of water. $T_{wall} = T_{sat}$ limits data were obtained for selected combinations of these conditions and are reported in Refs. 7, 9, and 15.

TRAC RIG FA MODEL

Figure 2 is a schematic of the TRAC model used to represent the Rig FA test facility. TRAC FILL components were used to inject liquid with known conditions into the random inlet. We also used BREAK components at the test section exit to provide outlet pressure boundary conditions. The bypass loops shown in Fig. 1 were not modelled specifically as experimental observations had indicated that there was no liquid flow in these lines at powers below thermal excursion.

We used a TRAC VESSEL component with 25 axial levels, 4 theta sectors, and 2 radial rings to model the test section and random inlet. The axial flow area of the outer ring varies consistently with the test section geometry. There is no flow in the inner ring. Subchannel or sector boundaries were chosen such that they coincide with the ribs. Azimuthal flow past the rib gaps is allowed between sectors. As shown in Fig. 2, Levels 1 and 2 model the exit region, Levels 3–17 model the heated test section, and Levels 18–25 model the random inlet. Flow eccentricity, similar to that assumed by SRL for the Mark-22 assembly,[20,22] was modeled by computing sector axial flows assuming two adjacent rib gaps had closed. Azimuthal flow was allowed even for this eccentric case.

Four TRAC HEAT STRUCTURES, each with 15 axial levels, are used to model the flame-sprayed heater. Radially, each heat structure was modelled with seven nodes. Three nodes were used to represent the base aluminum, and four nodes were used to model the flame-spray heater layer. The thermal conductivity of the flame-spray layer was determined to be 3.387 W/m°C based on data in Refs. 7, 9, and

15. Total power supplied to the heater was provided in the experimental data. The adiabatic heatup tests documented in Ref. 5 enabled us to compute both axial and azimuthal (sector) power distributions. Figure 3 shows thermocouple heatup rates for one of the Rig FA adiabatic heatup tests. The azimuthal and axial power profiles used in our TRAC model were obtained by normalizing these data. As indicated in Fig. 3, although Rig FA was intended to have a uniform axial and azimuthal power profile, a slight power tilt was present as subchannel B received about 5% more power than Subchannel C. This slight power tilt is reflected consistently throughout the $T_{wall} = T_{sat}$ test data as subchannel B was most often limiting.

For a given liquid flow, inlet liquid temperature, and assembly pressure difference, power was increased using a PID (proportional+integral+differential) controller to achieve steady-state power such that the limiting point on the heater surface just equalled the saturation temperature based on the assembly exit pressure. For most flow conditions, steady-state was achieved within a 40-s transient.

TRAC CODE MODIFICATIONS

Initial TRAC calculations indicated a need to modify the TRAC constitutive models to better simulate the effect of noncondensible gas (i.e., air) on heat transfer and fluid flow for downflow in narrow ribbed annuli. Wall-shear and interfacial-shear models[23] were developed and implemented in TRAC-PF1/MOD3 specifically for modelling two-phase air-water downflow in narrow ribbed annuli. These models were benchmarked using prototypical experiments performed by SRL. TRAC benchmark calculations for pressure drop, air entrainment, and void fraction were generally in good agreement with the experimental data as shown in Ref. 23.

SRL used the Rig B heated annulus experiments[19] to compute a heat-transfer correlation for use in FLOWTRAN-TF[20,21] that was suitable for air-water downflow in narrow ribbed annuli. We independently developed a heat-transfer correlation suitable for use in TRAC that was based on a best fit of the Rig B data.[16] The best fit of the data yielded a correlation that was a function of superficial liquid flow, liquid temperature, and hydraulic diameter. Oddly, the data did not correlate with phasic liquid or air velocity.

SUMMARY OF TRAC RESULTS

As discussed previously, the Rig FA adiabatic heatup tests[5] provided a basis on which to determine the axial and azimuthal power profiles. Figures 4 and 5 compare typical TRAC heater temperature calculations wi . experimental measurements for Test 1025. The data shown are for the 0.3658-m and 3.4138-m axial levels as measured from the bottom or exit of the test section. As shown in Figs. 4 and 5, the TRAC calculations closely match the experimental data, indicating that the TRAC model of the flame-spray heater is credible.

Reference 3 indicated that the experimental single-phase pressure drop for 12.1 gal./min was about 7.9e-03 psi/in. A TRAC simulation using the new constitutive models for wall shear[23] yielded a single-phase pressure drop of 7.83e-03 psi/in. for the same test conditions. This result supports our use of the maximum of the modified Churchill and modified Blasius equations[23] for calculating the single-phase friction factor.

Two-phase unheated Rig FA experiments are reported in Ref. 8. Comparisons of TRAC calculations with experimental data for air entrainment for two assembly dp's are presented in Fig. 6. TRAC appears to over-predict air entrainment for liquid flows above 4 gal./min. Below 4 gal./min, when annular flow is observed experimentally, both TRAC and the data indicate little to no air entrainment.

Typical axial pressure profiles computed by TRAC are compared with experimental data in Fig. 7 for the 6- and 12-gal./min unheated tests. Again, both TRAC and experimental data indicate little holdup of water in the upper portion of the random inlet. Note that less holdup of water is predicted for the 6-gal./min case as compared with the 12-gal./min case.

Figures 8–11 compare TRAC calculations of annulus fluid temperature and heater temperature with experimental thermocouple data for the 8-gal./min single-phase heated test and 8-gal./min two-phase heated test, respectively. The total assembly power was slightly more than 54 kW in both tests. For both tests, the TRAC-calculated annulus temperatures agree closely with the theoretical energy balance and with the experimental data. Interestingly, comparisons of the data in Figs. 9 and 11 show that higher heater temperatures occur in the single-phase tests. The lower outlet heater temperatures for the two-phase tests are clearly attributable to enhanced heat transfer because of increased phasic liquid velocity. However, as discussed previously, the effect of airflow is not accounted for in the TRAC forced-convection correlation based on Rig B data. However, note that TRAC does a credible job of predicting heater temperatures near the bottom of the test section for the two-phase case as shown in Fig. 11. Axial and azimuthal variations in both heater and annulus fluid experimental temperatures are observed in nearly all tests, with single-phase tests exhibiting the least variations. Despite differences in radial and azimuthal power profiles as input to the TRAC model, the code does not predict the observed local experimental behavior but instead predicts the assembly average trend. The annulus fluid temperature comparison shown in Figs. 8 and 10 does indicate that both TRAC and the data suggest reasonable energy balances.

Experimental results provided in Ref. 3 indicated that air entrainment tended to decrease as heat increased. A series of tests, which are documented in Refs. 3 and 4, was performed to determine the effect of power on air entrainment for 8-gal./min liquid flow. TRAC calculations were performed for similar heated conditions and are compared with experimental data in Fig. 12. Figure 12 presents air entrainment vs assembly outlet liquid temperature, which is related directly to assembly power. In Fig. 12, two TRAC calculations are presented. The curve designated "TRAC-heated" represents heated assembly tests that replicated the test data. The curve designated "TRAC-unheated" represents the results of unheated air entrainment calculations with water injected at increasing temperatures. Injecting warm water results in decreased entrainment, probably as a result of increased partial pressure. Clearly, TRAC over-predicts the effect of heating on air entrainment except at high powers, when saturation conditions are reached in the assembly and entrainment decreases to near zero. No satisfactory explanation of the effect of heating on air entrainment has yet been developed.

As indicated previously, a series of parametric test were undertaken[7,9,15] to determine $T_{wall} = T_{sat}$ limits for a range of liquid flows (4–14 gal./min), inlet liquid temperatures (30°C to 60°C) and assembly pressure drops (0.0 m. to -1.89 m H_2O). A total of 18 parametric tests was performed; however, this number was insufficient to really assess how well TRAC could predict the parametric effects. TRAC calculations were performed for each of these tests and are summarized in Figs. 13 and 14. Figure 13 shows $T_{wall} = T_{sat}$ power limits vs inlet liquid flow for nominal boundary conditions of 45°C inlet liquid temperature and -0.945 m H_2O assembly dp. As shown, TRAC-calculated powers agree favorably with the experimental data. The results of the parametric runs are included, and TRAC-calculated $T_{wall} = T_{sat}$ powers are compared with experimental measurements in Fig. 14. TRAC results were poorest for low liquid flows (i.e., 4 gal./min) with high assembly back pressures.

However, overall TRAC calculations for $T_{wall} = T_{sat}$ power limits closely followed the experimental data.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

In general, the TRAC calculations for the entire test series compared well with experimental Rig FA data over the range of test conditions. One exception to the generally excellent agreement between the code calculations and the test data was that TRAC did not appear to account for the effect of heating on air entrainment properly. We are investigating reasons for this difference. Fortunately, this problem has no real effect on TRAC's ability to compute $T_{wall} = T_{sat}$ power limits because air entrainment approaches zero as the liquid temperature approaches saturation. The overall excellent quality of the code-data comparisons demonstrates that TRAC-PF1/MOD3 with proper modeling is capable of simulating thermal-hydraulic phenomena typical of those encountered in a Mark-22 fuel assembly during LOCA/ECS conditions.

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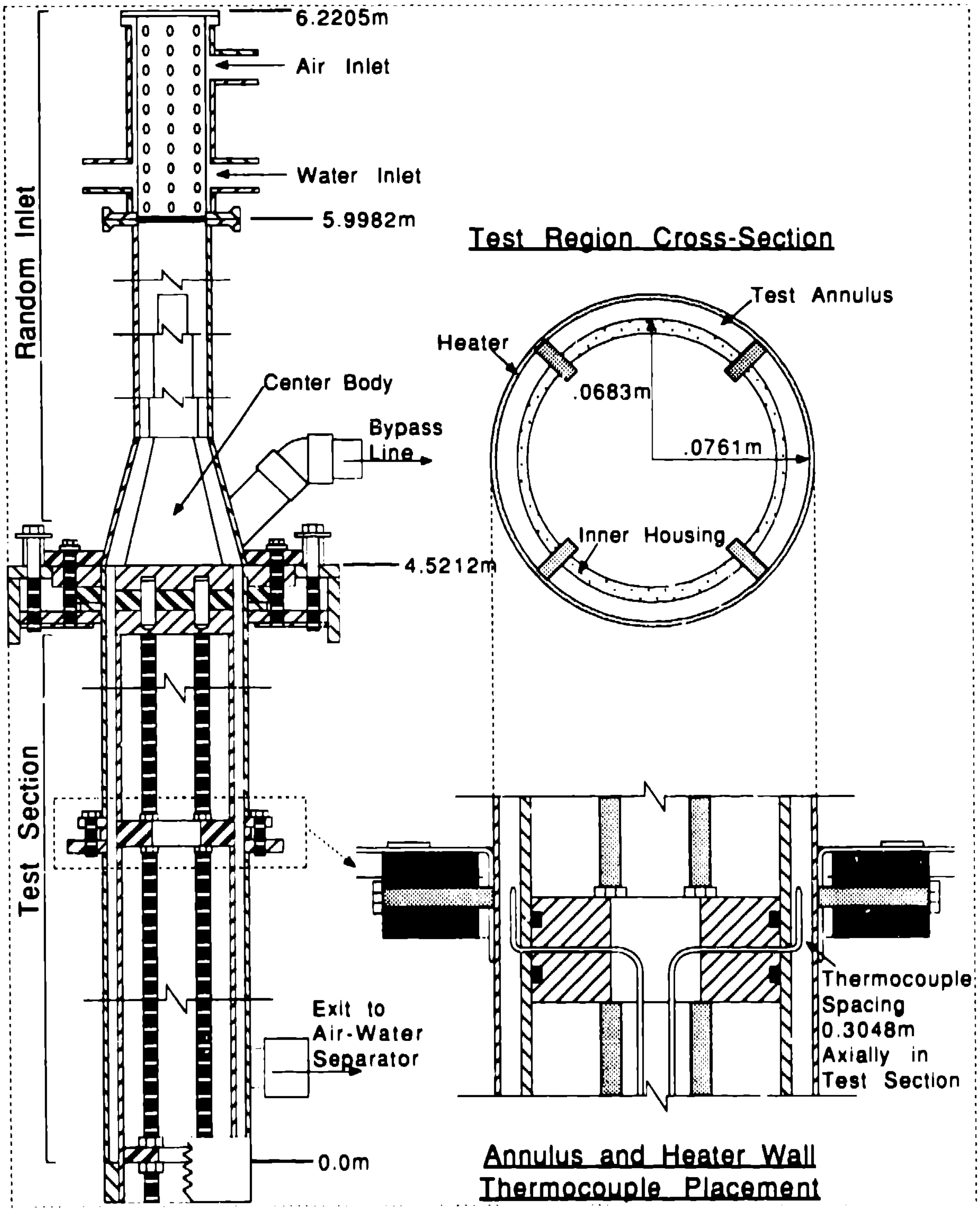

Fig. 1.
Rig FA experimental test facility.

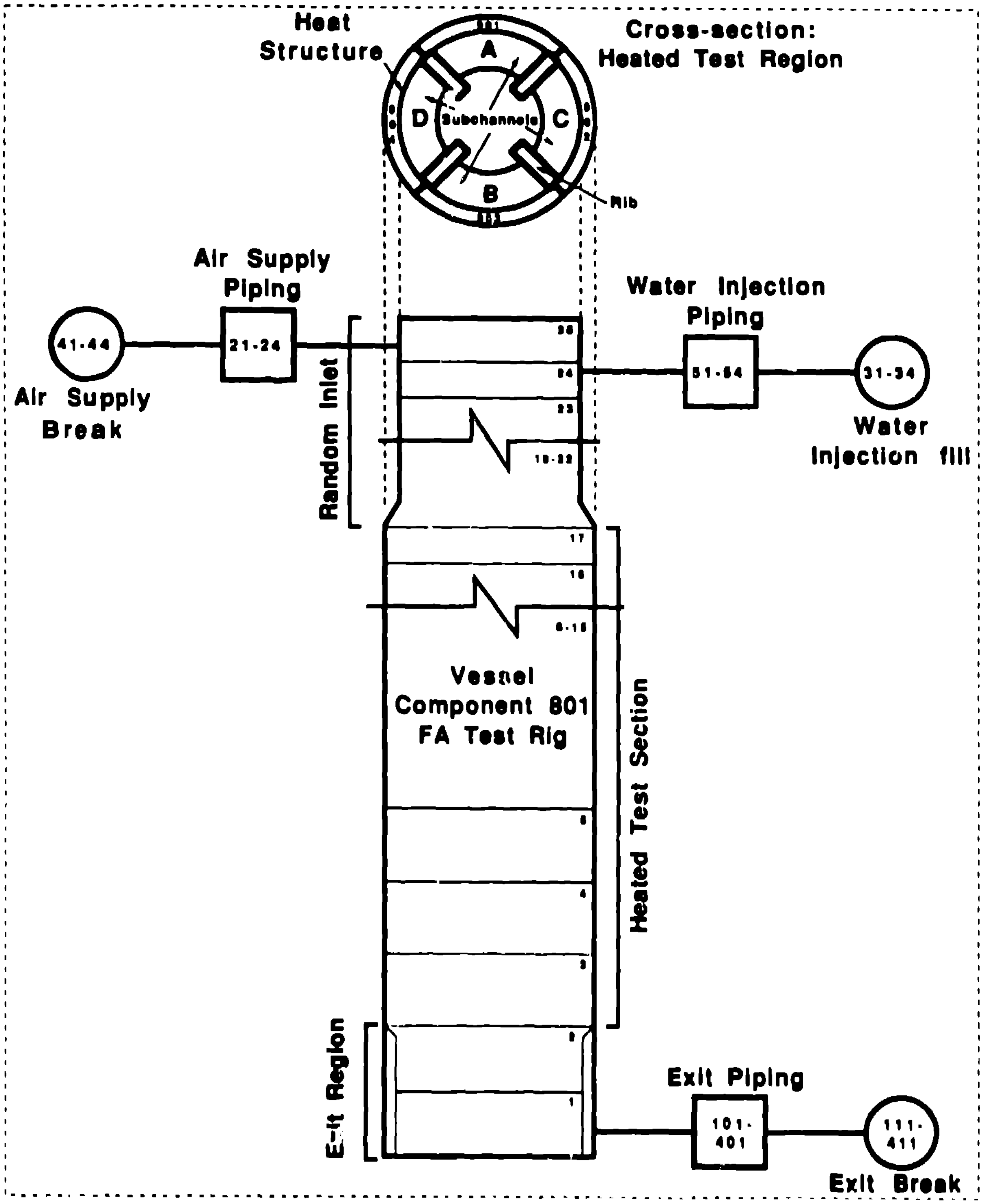

Fig. 2.
TRAC model of Rig FA.

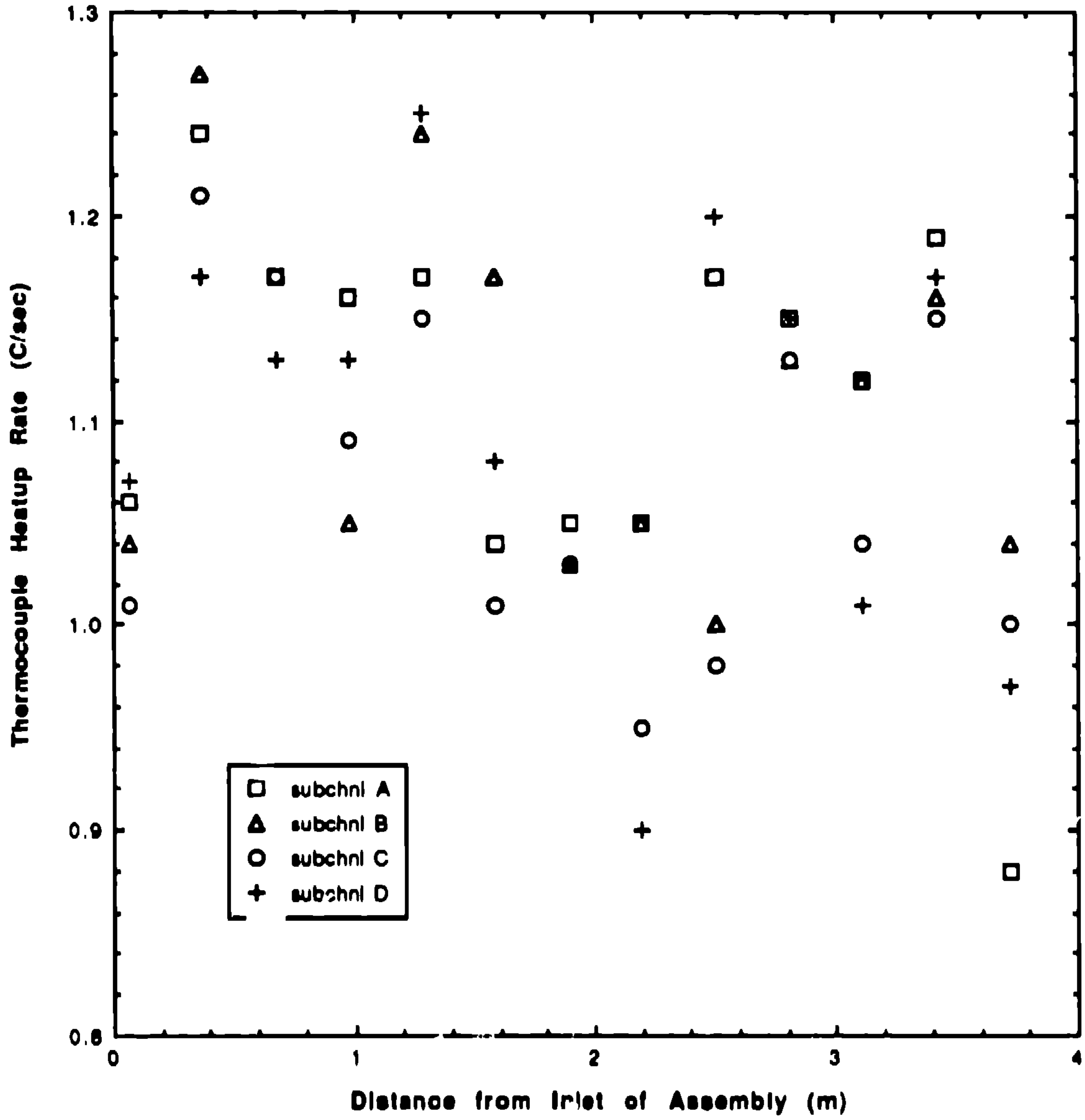

Fig. 3.
Thermocouple heatup rates for Rig FA adiabatic heatup Test 1025.

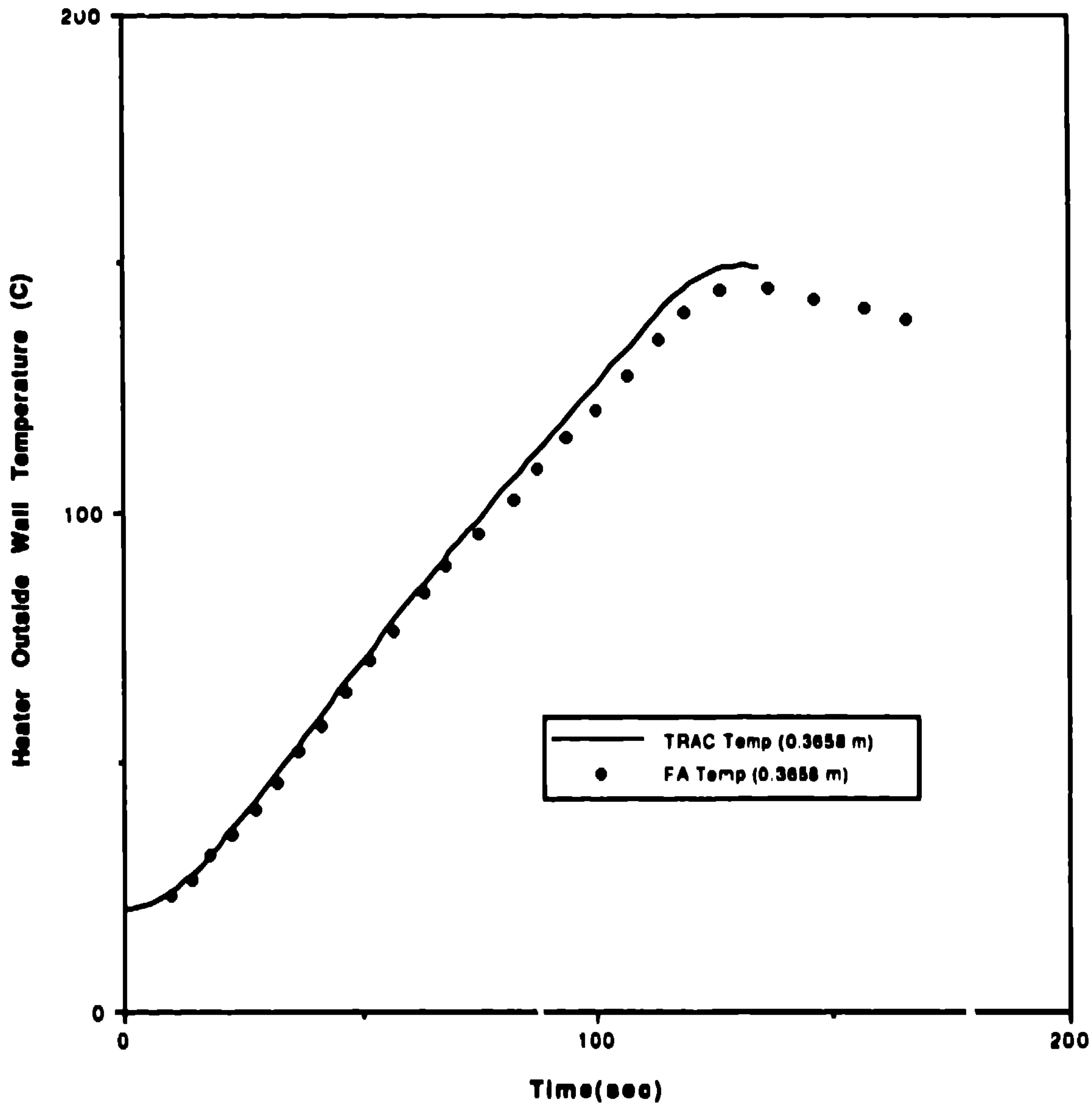

Fig. 4.
Rig FA adiabatic heatup Test 1025 comparison of TRAC and experimental data at 0.3658 m.

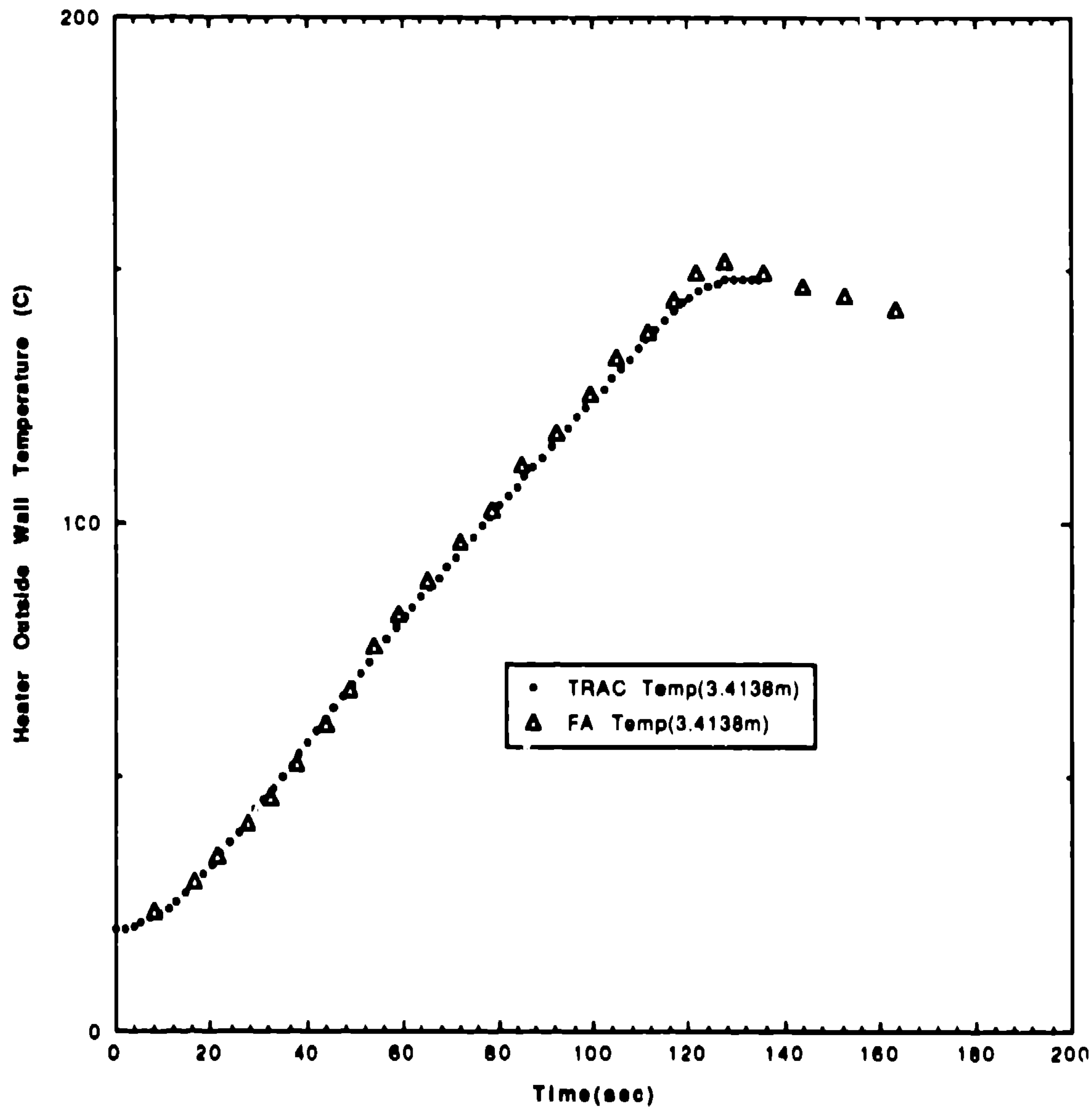

Fig. 5.
Rig FA adiabatic heatup Test 1025 comparison of TRAC and experimental data at 3.4138 m.

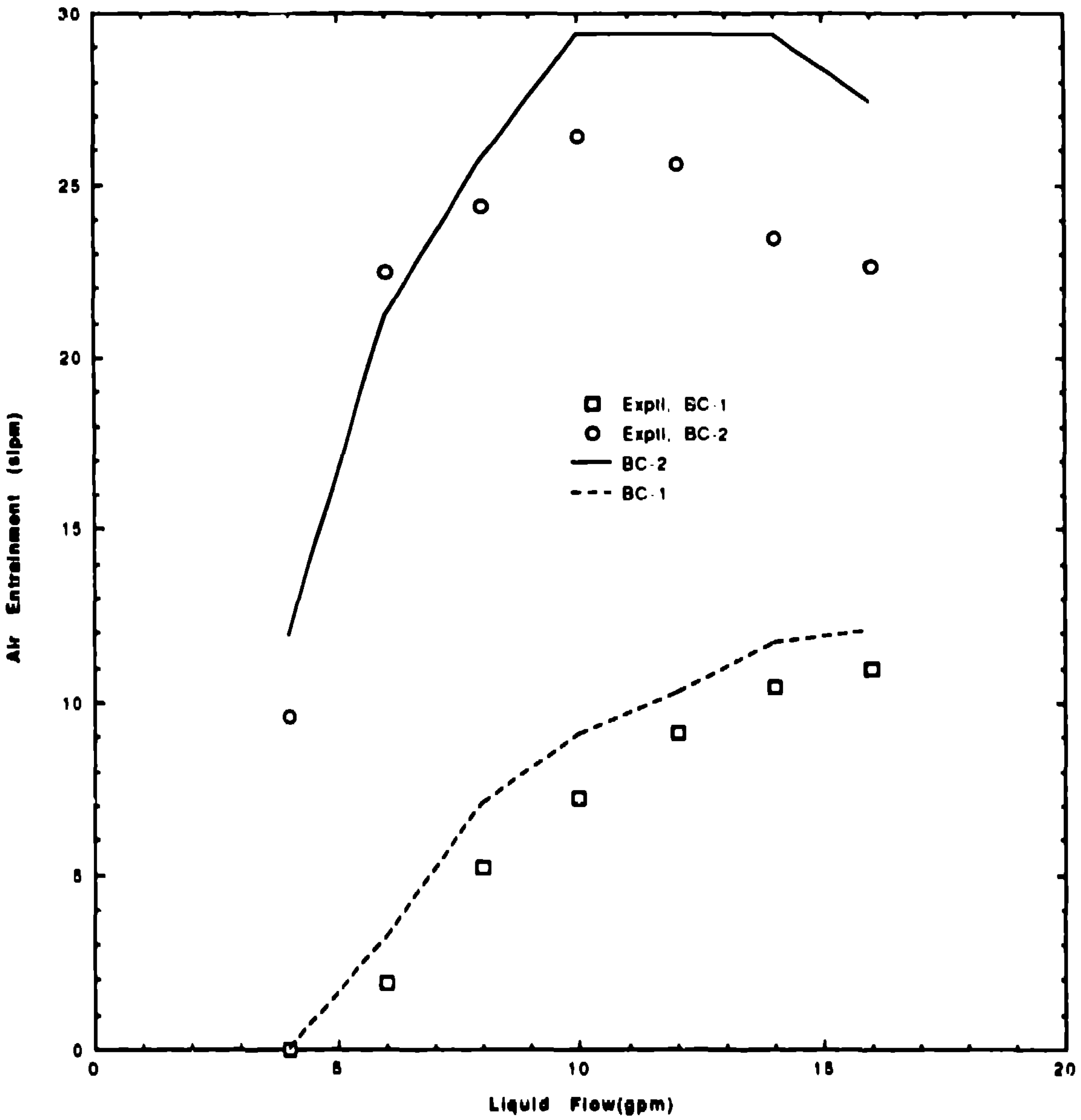

Fig. 6.
Rig FA unheated air entrainment test comparison of TRAC and experimental data BC-1 (Dp = -2.265 m H_2O) and BC-2 (Dp = -0.422 m H_2O).

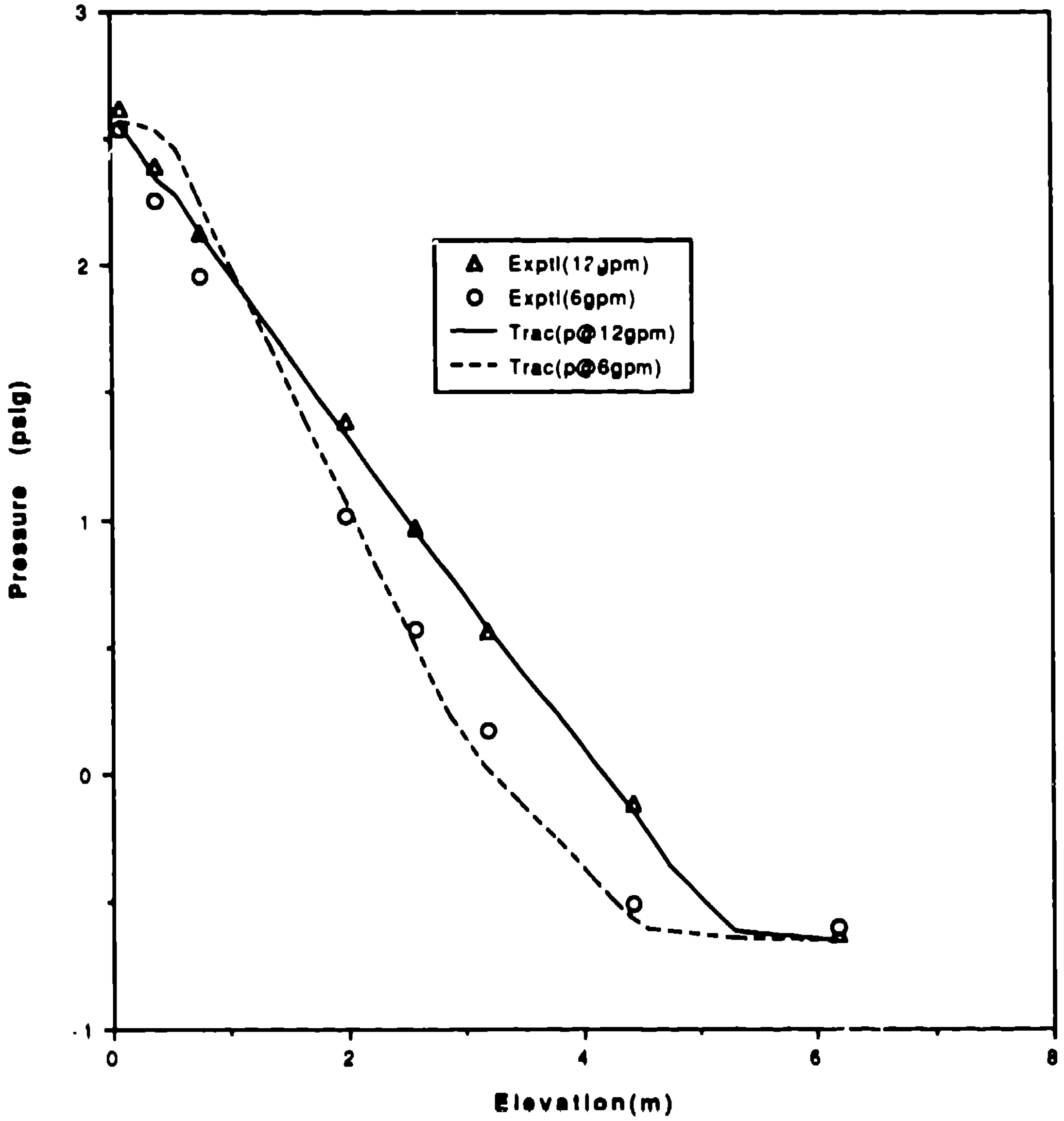

Fig. 7.
Rig FA unheated two-phase pressure-drop test comparison of TRAC and experimental data for 6 gal./min and 12 gal./min.

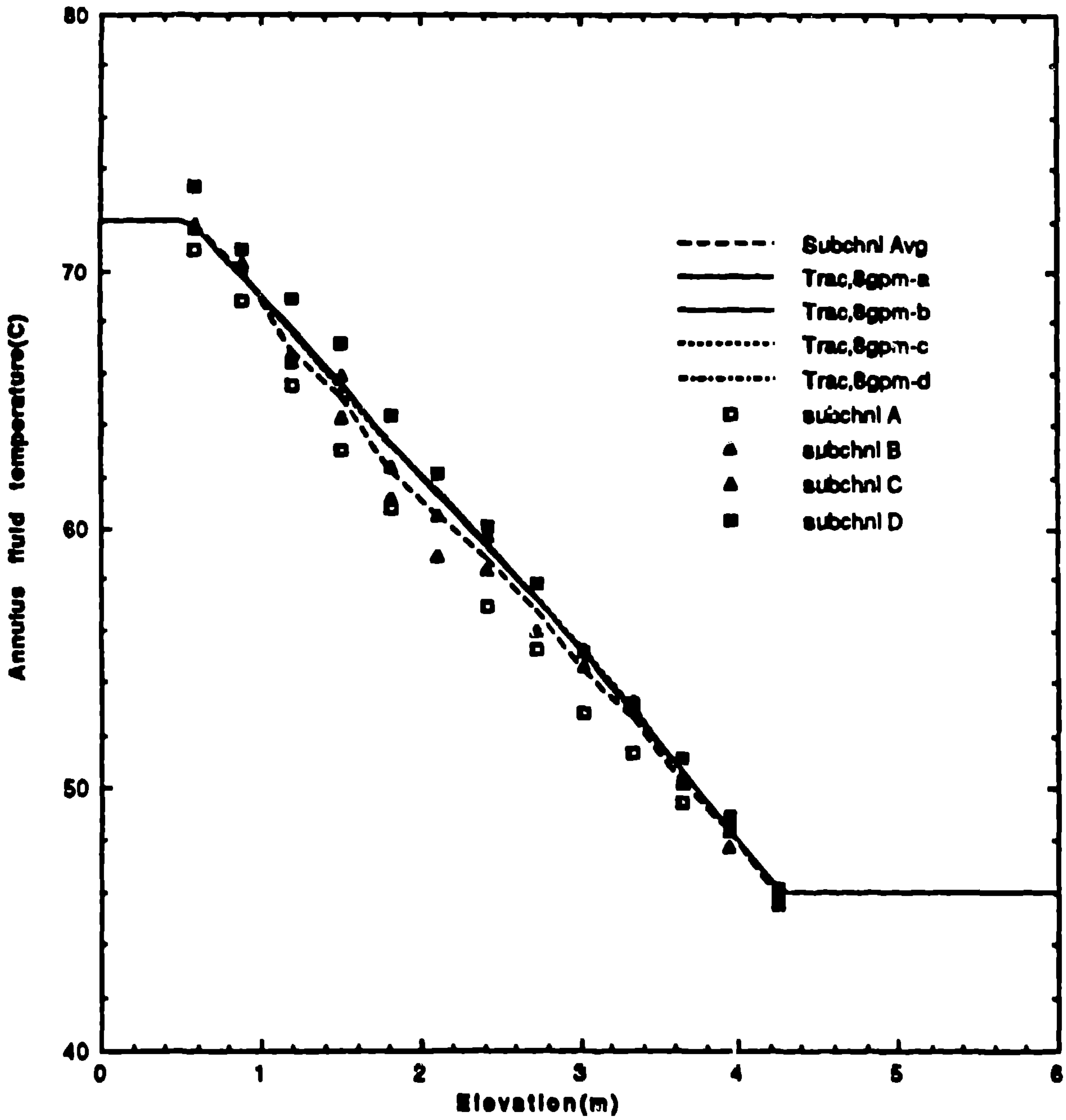

Fig. 8.
Rig FA single-phase heated tests (8 gal./min, 54.9 kW) comparison of TRAC and experimental annulus fluid temperatures.

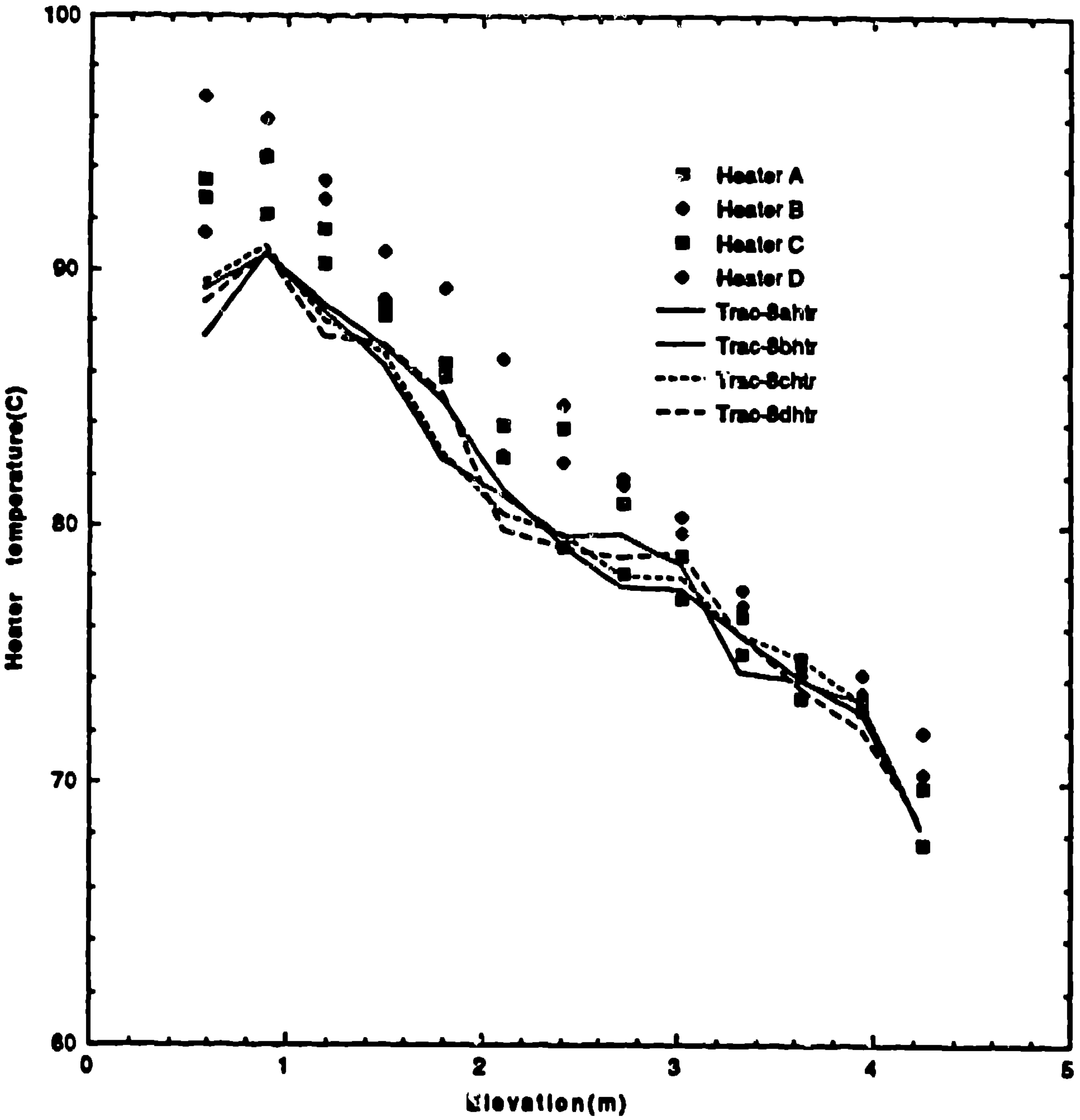

Fig. 9.
Rig FA single-phase heated tests (8 gal./min, 54.9 kW) comparison of TRAC and experimental heater temperatures.

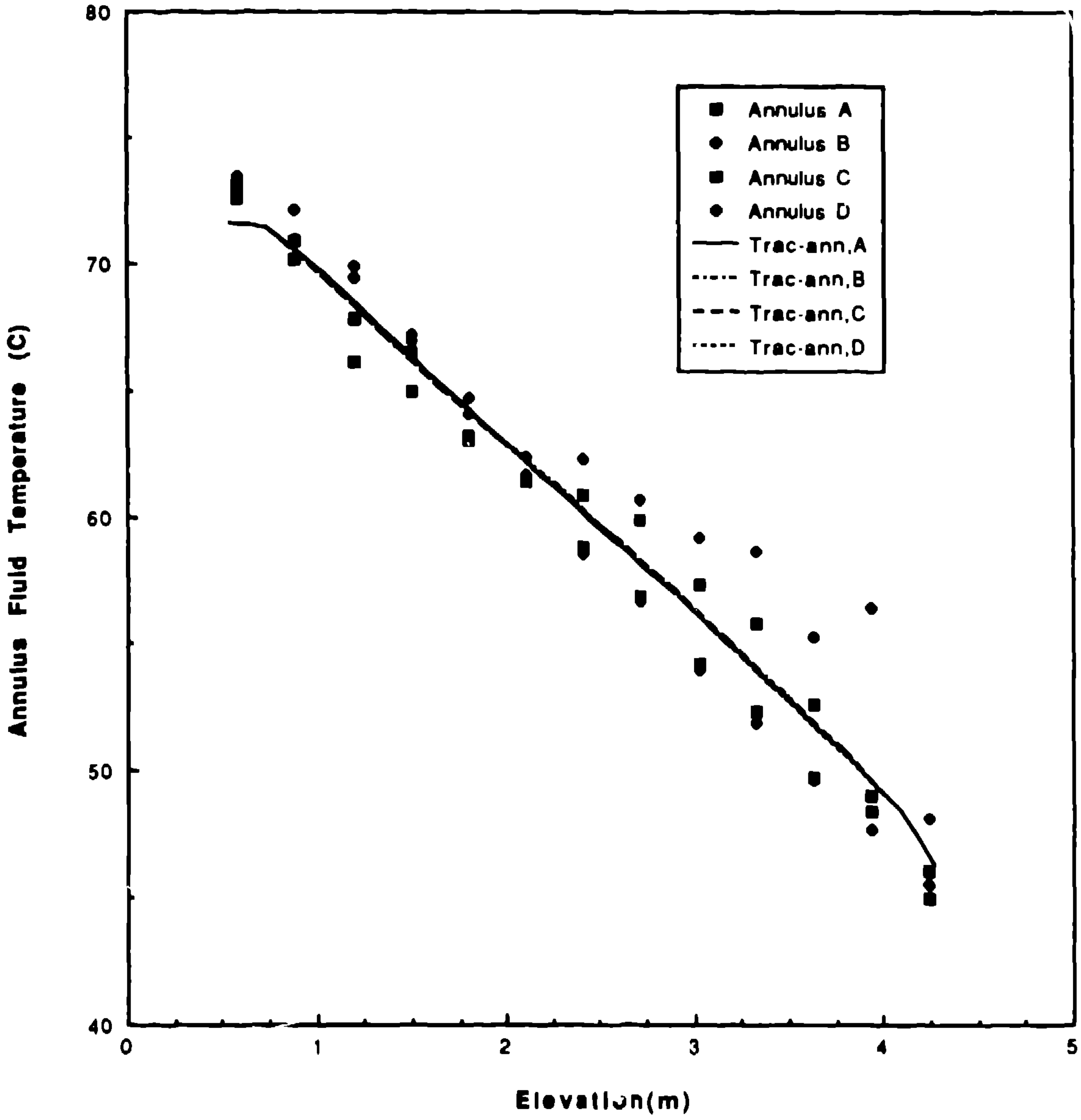

Fig. 10.
Rig FA two-phase heated tests (8 gal./min, 54.3 kW) comparison of TRAC and experimental annulus fluid temperatures.

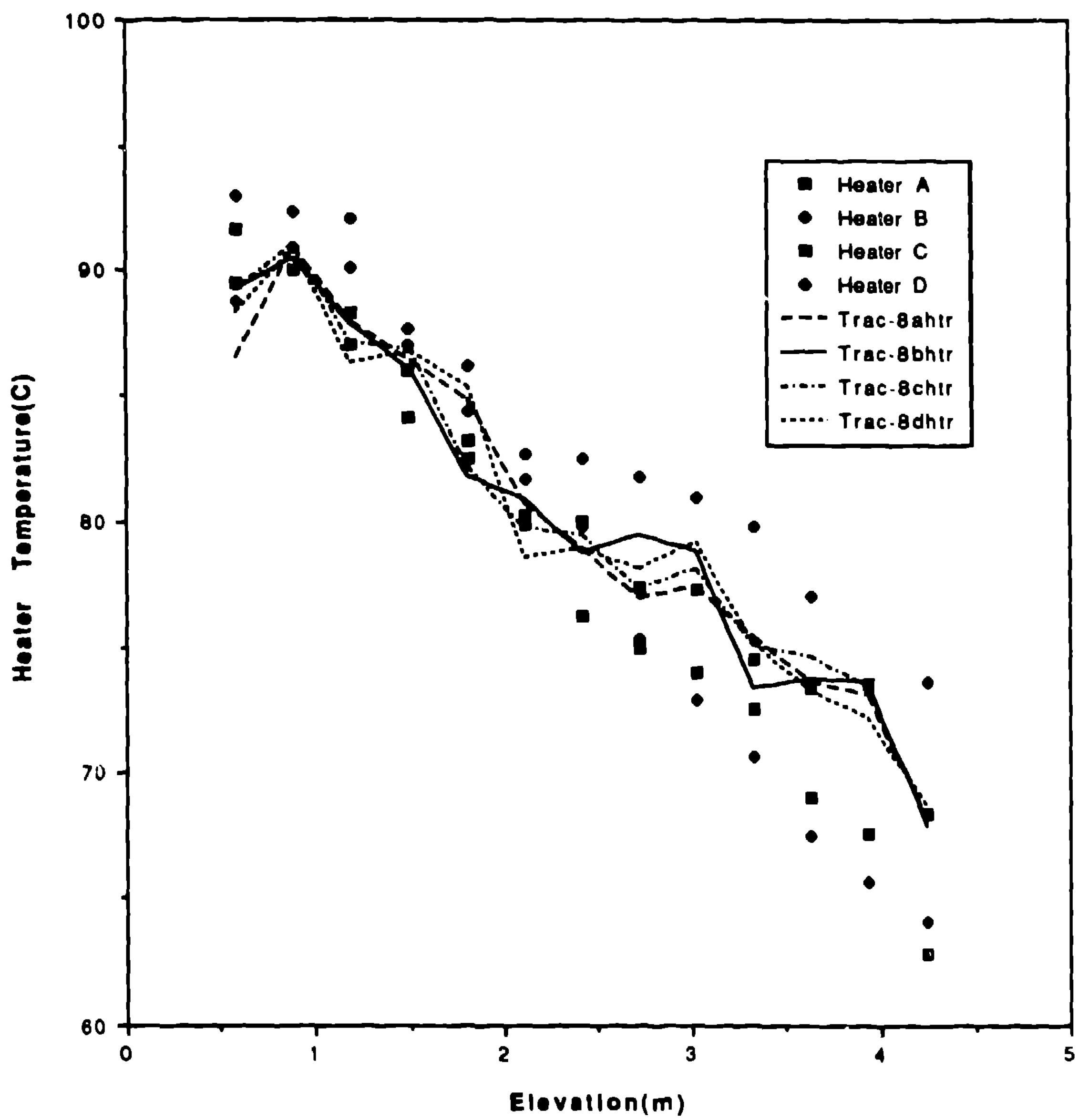

Fig. 11.
Rig FA two-phase heated tests (8 gal./min, 54.3 kW) comparison of TRAC and experimental heater temperatures.

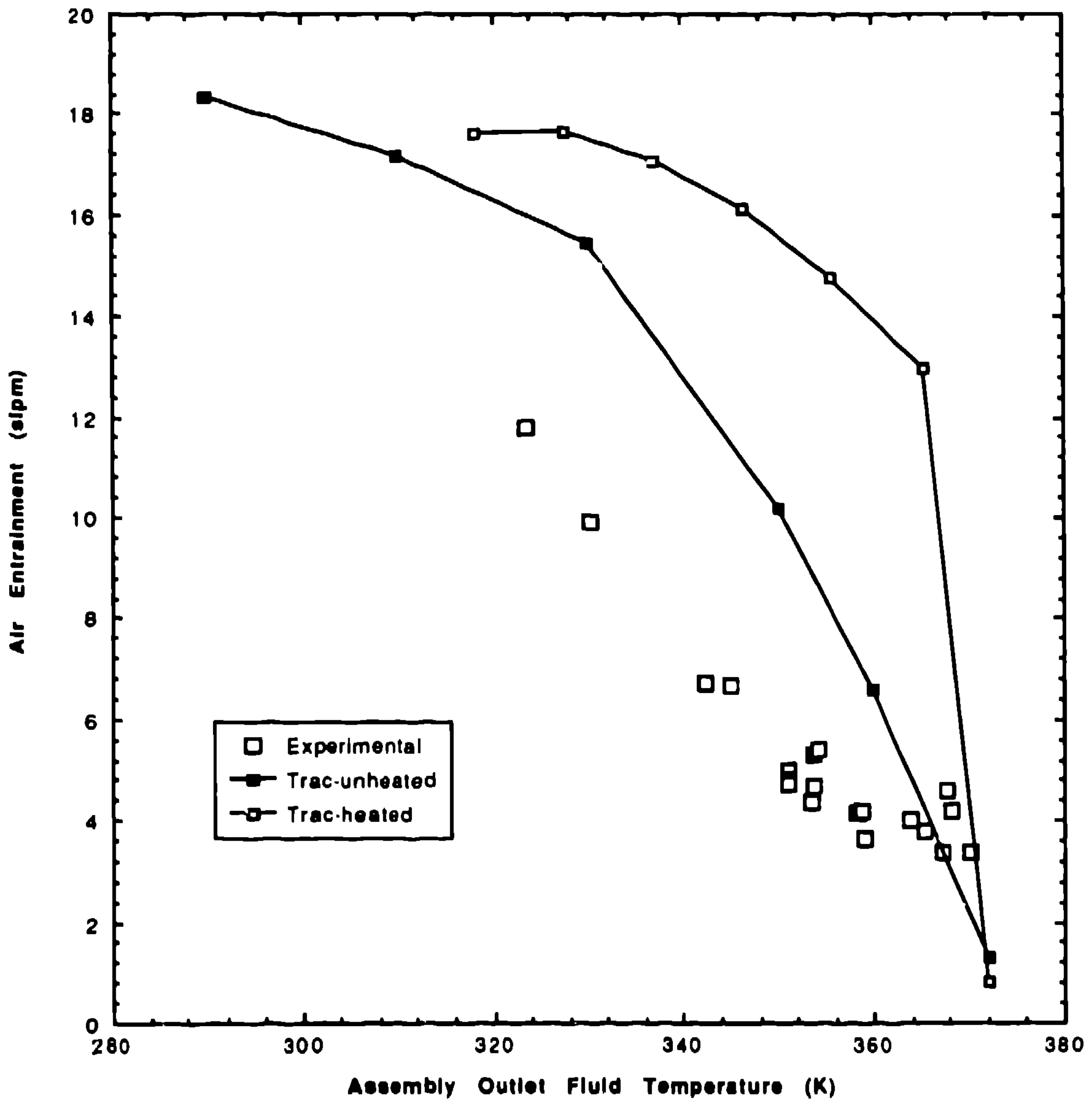

Fig. 12.
Rig FA effect of heating on air entrainment test comparison of TRAC and experimental results.

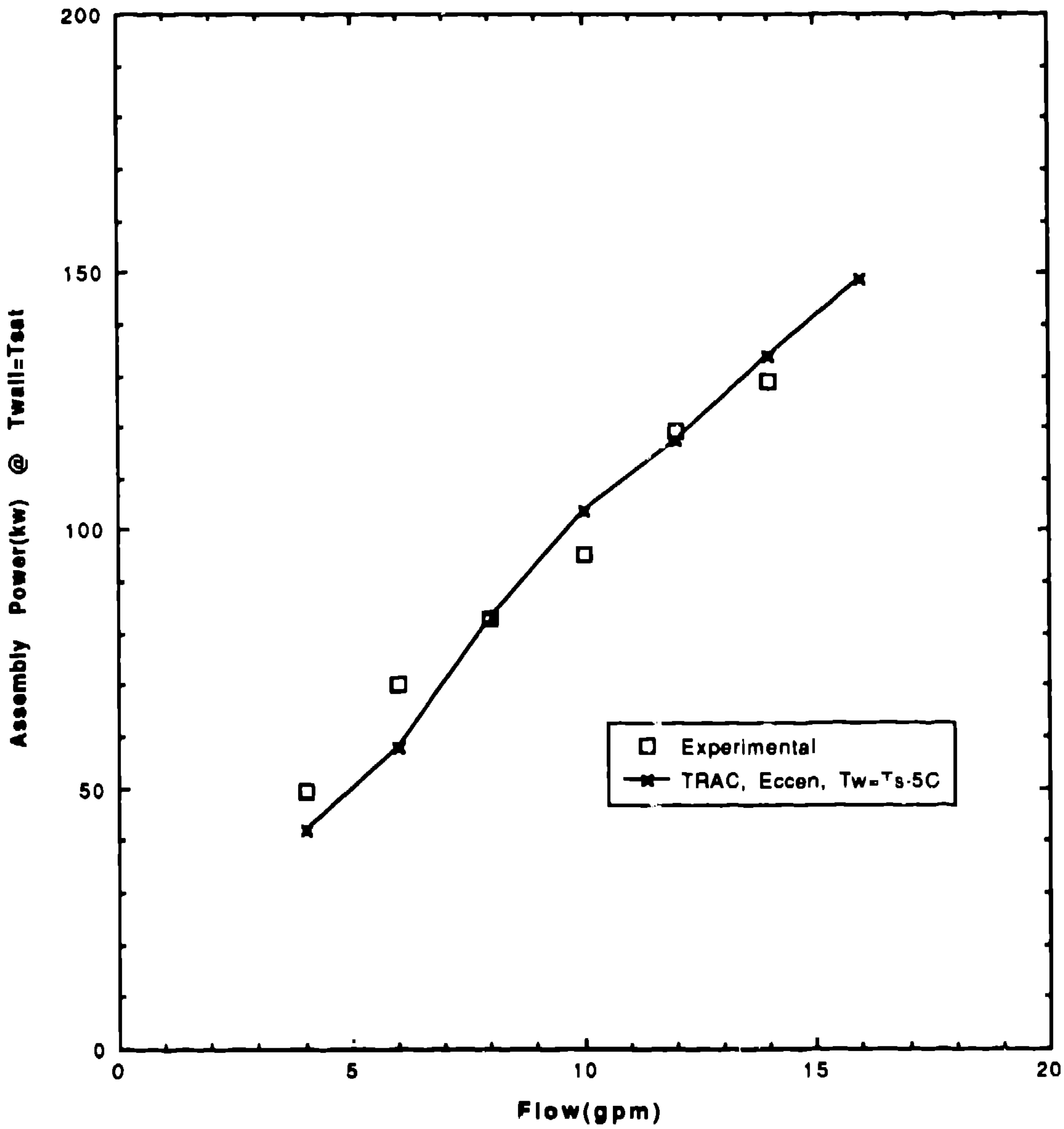

Fig. 13.
Rig FA T_{wall} = T_{sat} power limits vs inlet liquid flow test comparison of TRAC and experimental results.

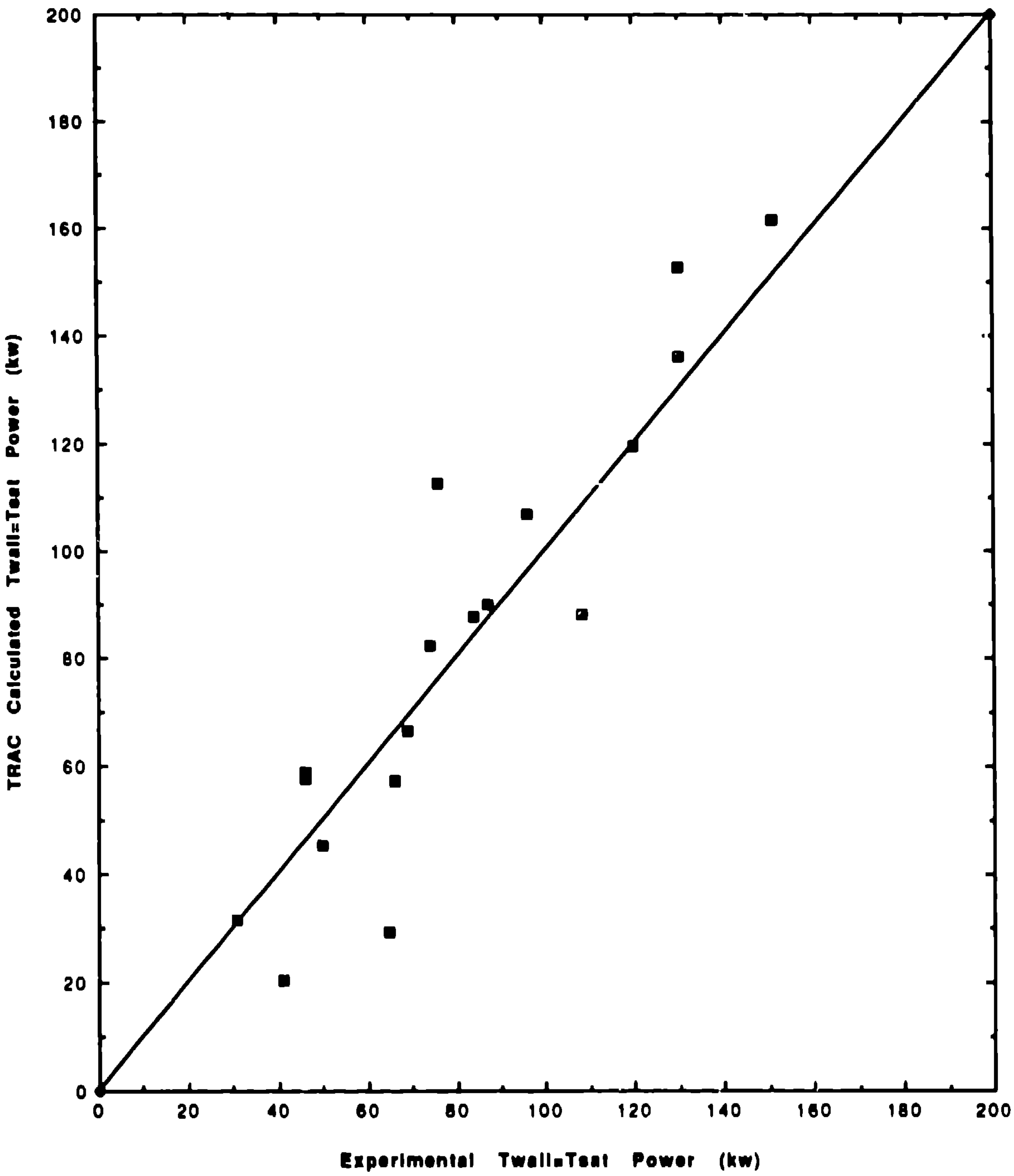

Fig. 14.
Rig FA parametric tests. TRAC calculated vs experimental $T_{wall} = T_{sat}$ power.