An Experimental Investigation of Thermal Stratification in Water-Filled Flasks

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ABSTRACT

Transport flasks are often filled with water as it provides both good cooling and shielding for irradiated fuel. However, during a fire, thermal stratification may occur, potentially leading to significant pressurisation of the flask from the vapour pressure of the water.

A series of 12 experimental tests into thermal stratification have been carried out, based upon the NEACRP thermal benchmark problem UK-4. The results show that under the conditions of the test, with the dry vessel walls above the water being heated, strong thermal stratification occurs and high internal pressures are generated. The vapour pressure inside the vessel is demonstrated to be related to the temperature of the water surface. The agreement with the calculated results of the benchmark problem is reasonably good, demonstrating that the methods used in the benchmark exercise can be used to adequately model thermal stratification in water-filled flasks.

INTRODUCTION

Transport flasks are often filled with water as it provides both good cooling and shielding for irradiated fuel. However, thermal stratification can occur in the water due to its buoyancy. This phenomenon may be particularly important during the IAEA Regulatory thermal test, when the heat flux from the fire, conducted through the walls of the flask, might produce significant temperature gradients in the water. This, in turn, may lead to significant pressurisation of the flask from the vapour pressure of the water. It is therefore important that the potential for thermal stratification to occur should be considered in any thermal assessment of a water-filled flask.

In 1987 a benchmark exercise was organised by the NEACRP in which heat transfer codes used internationally for the thermal assessment of transport flasks were tested on a set of standard problems. This benchmark exercise was reported at PATRAM '89 [1]. One of the problems submitted by the UK concerned the modelling of thermal stratification during the thermal test. The problem consisted of a vertical steel cylinder, partly filled with water, with a uniform heat flux applied to the outer vertical surface. The problem (identified as UK-4) is illustrated in Figure 1.

The water was expected to become thermally stratified, with the temperature always increasing with height, and under these conditions natural convection was expected to be largely inhibited and heat transfer in the water in the vertical direction to be dominated by conduction. Although Computational Fluid Dynamics codes might appear to be most suitable for modelling this type of problem, CFD codes were not included in the benchmark exercise. Participants were therefore requested to model the stratified water as a solid with an anisotropic conductivity. In the horizontal direction, an artificial, high value of conductivity was to be specified so that the temperature of the water would be almost uniform across any horizontal plane. In the vertical direction, the true thermal conductivity of water was to be specified.

When the benchmark problem was proposed, it was stated that an experiment might be performed against which the analytical solution could be validated. Experimental tests were, in fact, carried out in 1988, but the results were not available until after the final report of the benchmark exercise had been issued and were never reported in the open literature. The experimental data is therefore being reported in the current paper so that it can be used and referenced in flask thermal assessments.

DESCRIPTION OF THE EXPERIMENTAL RIG

The experimental rig, called the Transient Stratification Rig, represented, as closely as possible, the benchmark UK-4 problem. It was not possible to duplicate the benchmark problem exactly because the vessel in the problem was idealised and not designed as a pressure vessel.

The rig is shown in Figure 2. It was designed as a pressure vessel capable of being pressurised up to 44 bar. It consisted of a cylindrical mild steel vessel closed at the top with a domed steel cap and at the bottom by a thick steel plate which was bolted to the vessel. Pipework was connected to the top of the rig for vacuuming and filling with nitrogen, and to the bottom for draining and filling with water.

The vessel was heated on the outer vertical surface by electric heater tapes arranged in three zones. These were capable of providing the heat flux of 10 kW/m^2 specified in the benchmark problem and gave a maximum total heat input to the rig of 6 kW. The outer surface of the vessel and pipework were lagged. In the benchmark problem a cooling phase was included, during which there was heat loss from the vessel by natural convection and radiation. This phase, which was not thought to be as important as the heating phase, was not modelled in the Transient Stratification Rig, thus avoiding the need to rapidly remove the insulation.

The temperature of the rig was measured by 40 type K thermocouples. Sixteen were attached to the outer surface of the vessel to record the wall temperature at different heights. Twenty three were passed into the vessel through seals in the bottom plate and measured the temperature of the water. Most of these were on the centre-line, at different heights, but some measured the temperature variation with radius. One thermocouple recorded the ambient air temperature. The locations of the thermocouples are shown in Figure 2. The temperatures of all the thermocouples were recorded on a data logger at 30 second intervals. The current and voltage to the heaters and the internal pressure in the vessel were also recorded by the data logger.

THE TEST PROGRAM

The test program consisted of a series of 12 tests. These covered a range of heat fluxes (5 or 10 kW/m^2) and heated zones, initial pressure (1 bara of nitrogen or vacuum) and both a constant and a changing water level. The water level was kept constant in most of the tests to enable the water temperature profile near the surface, and especially the water surface temperature itself, to be measured more accurately by avoiding movement of the thermocouples relative to the water surface. This also replicated more accurately the benchmark problem, which did not include any movement of the water level due to thermal expansion of the water.

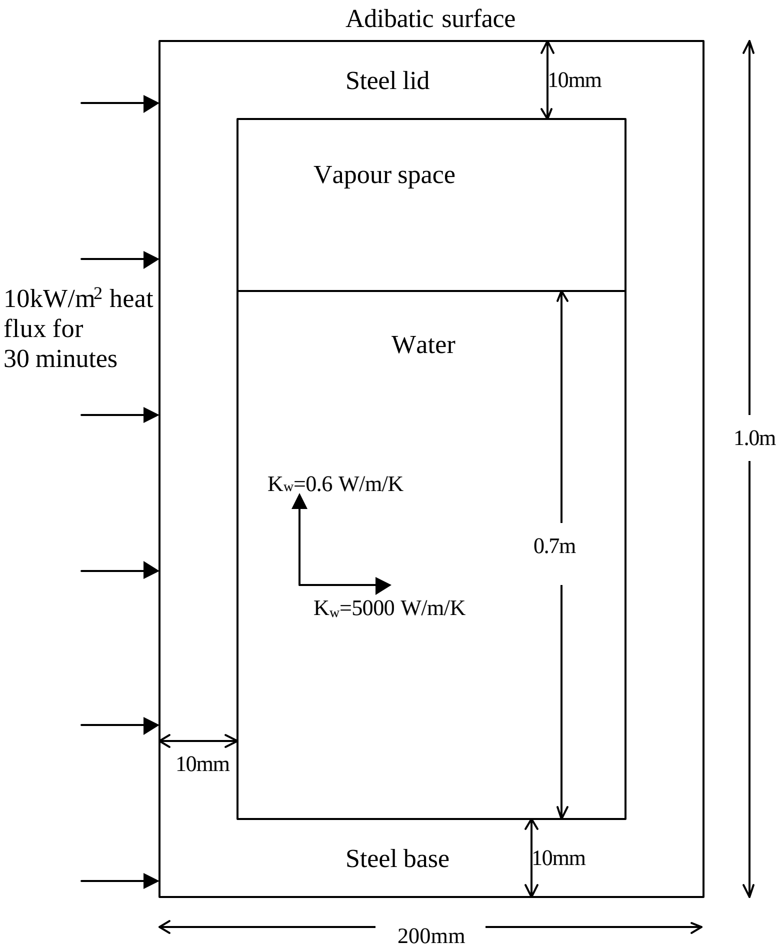

Figure 1 – The Benchmark Problem UK-4

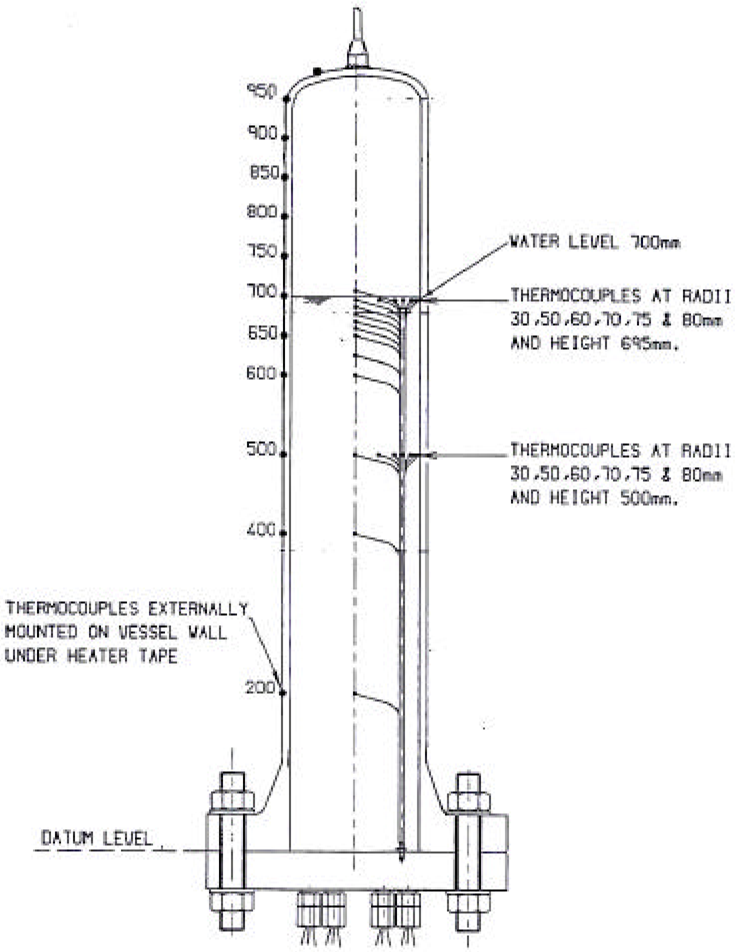

Figure 2 – The Transient Stratification Rig

Tests 2, 3, 4, 6 and 7 all represented the benchmark problem UK-4. This test was repeated several times in order to demonstrate reproducibility. Tests 2, 3 and 4 all suffered from heat loss due to condensation in the pipework. This was rectified after test 5.

RESULTS

Strong thermal stratification of the water was observed, as expected. The surface of the water became very hot, producing a high pressure inside the vessel, while the temperature of the water at the bottom of the vessel changed very little. This can be clearly seen in Figure 3, which shows temperatures at different heights as a function of time, and Figure 4 which shows the vertical temperature profile of the water, after 30 minutes, in test 6. In this test the heaters were turned off after 30 minutes. Also shown in Figure 4 is the temperature of the steel vessel. The temperature difference between the vessel and the water can be seen to be small compared to the temperature variation in the water itself. At two heights several thermocouples were placed at different radii. These showed the temperature of the water to be virtually constant in the radial direction.

In test 11, the vessel was only heated below the water surface level. The resulting temperature profile, at 30 minutes, is also shown in Figure 4. It can be seen that in this case there was very little thermal stratification of the water and the resulting pressure inside the vessel was significantly lower than that obtained in the other tests. This demonstrates the importance of the dry upper part of the vessel in conducting and radiating heat down to the surface of the water.

The importance of considering the potential for thermal stratification in a transport container during a fire test is related to the effect that it has upon the internal pressure in the container. It was expected that the total pressure would be equal to the pressure from heating and compressing the gas in the ullage space added to the vapour pressure from the water vapour. This vapour pressure was expected to correspond to the temperature of the water surface. The data from the Transient Stratification Rig validates this assumption. Figure 5 shows the measured pressure during two runs, one starting with 1 bar of nitrogen internal pressure and the other with vacuum. Also shown is the predicted pressure. The contribution from the water vapour pressure was based on the measured water surface temperature. The nitrogen gas was also assumed to be at this temperature. Since the water level was kept constant, there was no pressure due to compression of the nitrogen. The measured and predicted pressures can be seen to be in good agreement proving that the vapour pressure in the vessel is controlled by the water surface temperature, as expected.

In tests 9 and 10, the water level was not kept constant but instead was allowed to rise as the water expanded. Because the water level was changing with time, the water surface temperature is unknown. However, it has been shown that the water surface temperature can be related to the pressure inside the vessel. The pressure measured in test 9 is shown in Figure 6. Also shown is the pressure measured during test 6 which was identical except for the water level being kept constant. It can be seen that with the water level allowed to rise, the pressure in the vessel is higher. This increase corresponds to an increase in water surface temperature of about 14°C at 30 minutes.

COMPARISON WITH THE BENCHMARK EXERCISE

The temperatures calculated by AEA Technology using the TAU Finite Element code [2] were shown to be in good agreement with other submissions to the benchmark exercise [1]. The TAU

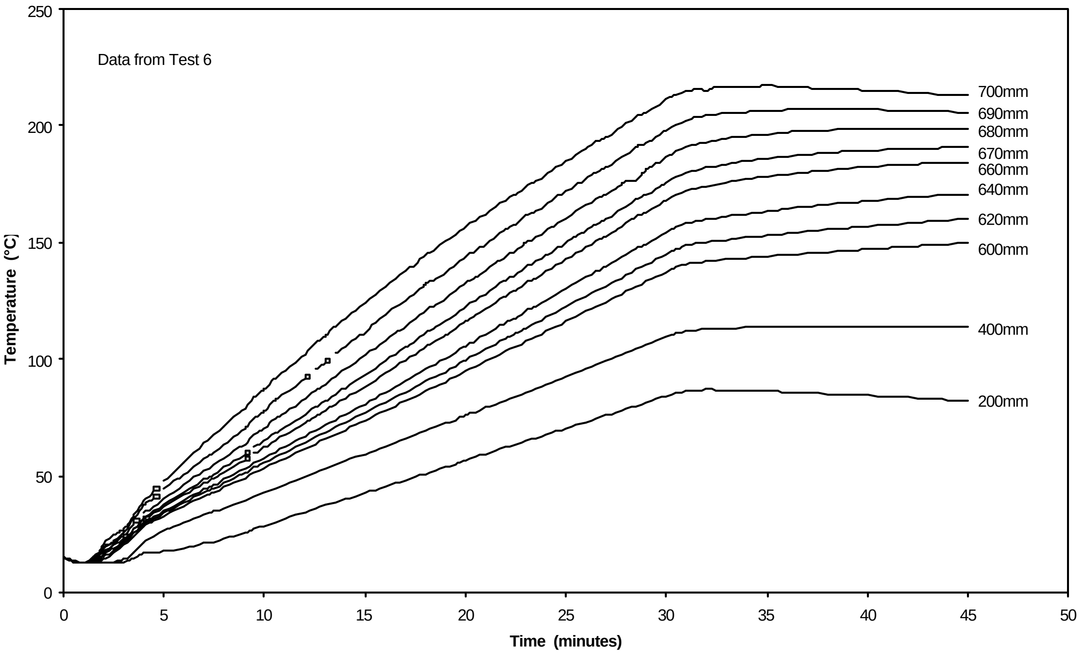

Figure 3 – Water Temperature at Different Heights

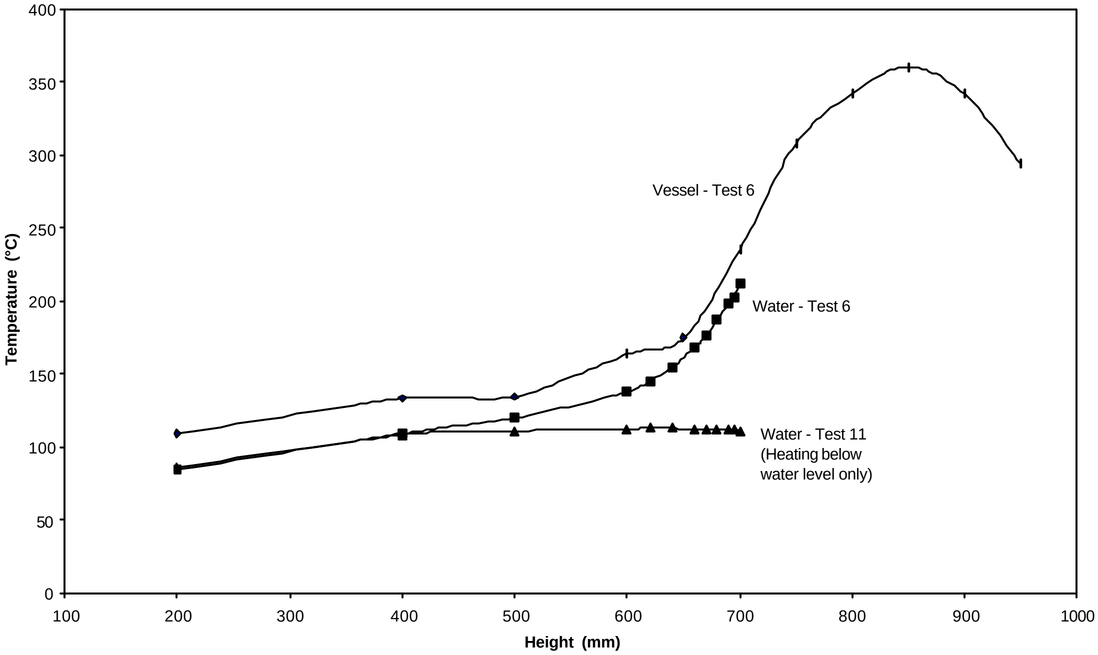

Figure 4 –Temperature Profile in the Water and Vessel at 30 Minutes

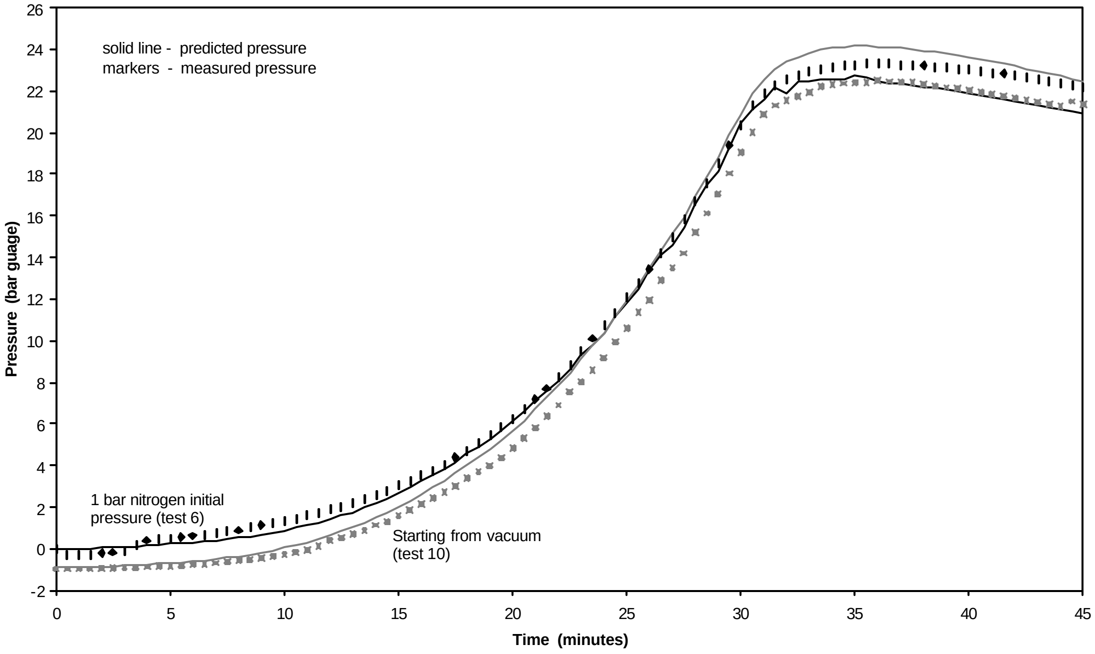

Figure 5 –Measured and Predicted Internal Pressure

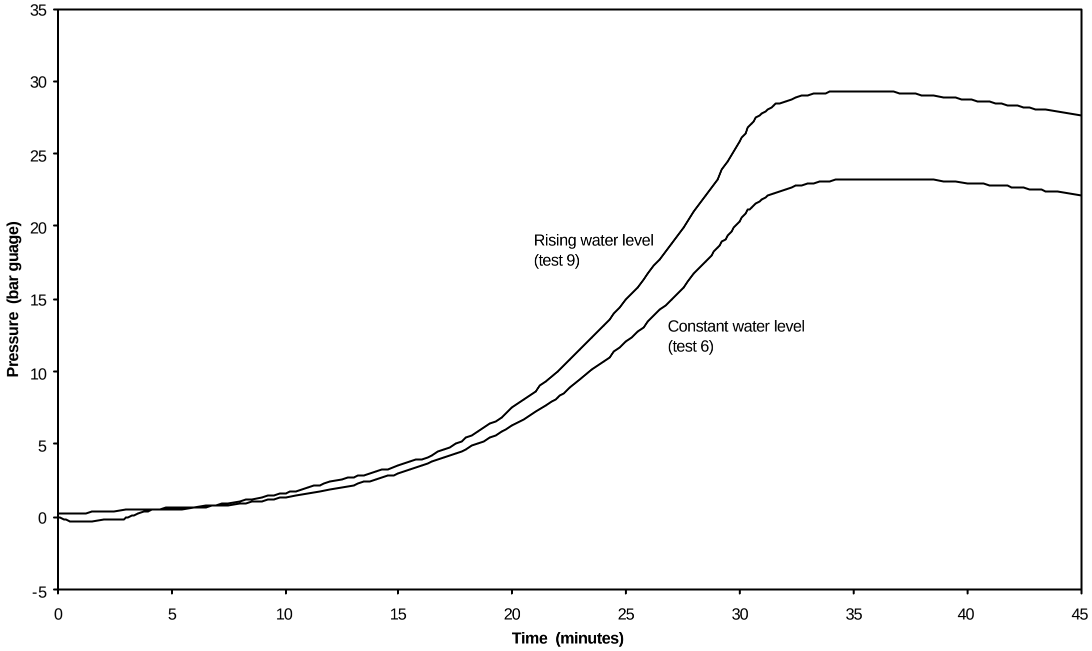

Figure 6 – The Effect of Water Expansion on Internal Pressure

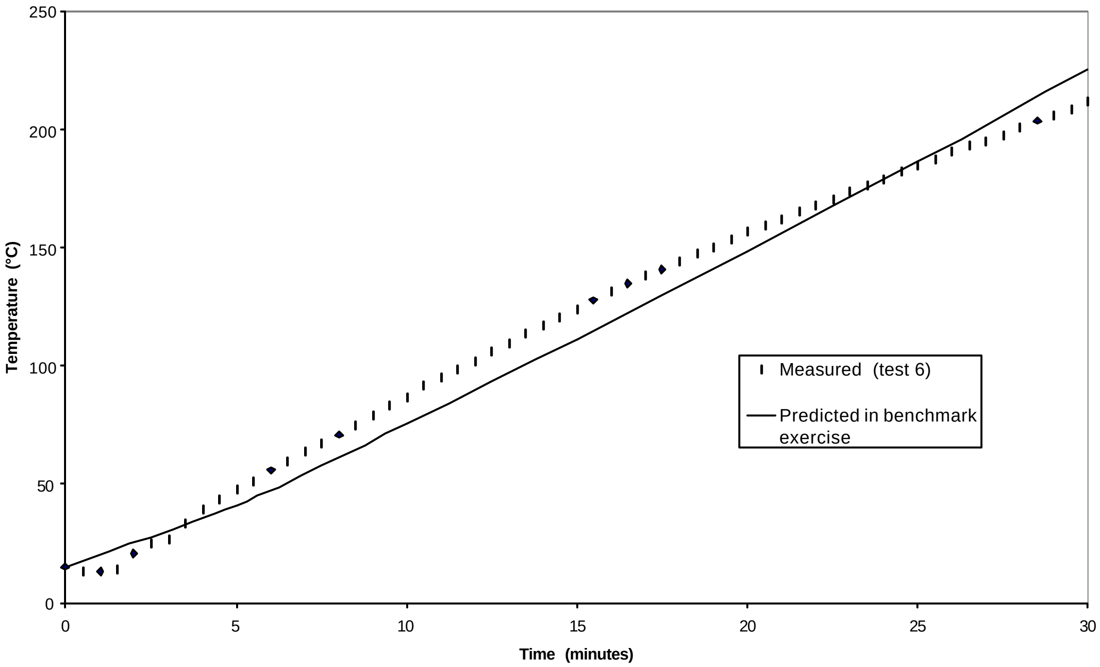

Figure 7 – The Water Surface Temperature in the Benchmark Test

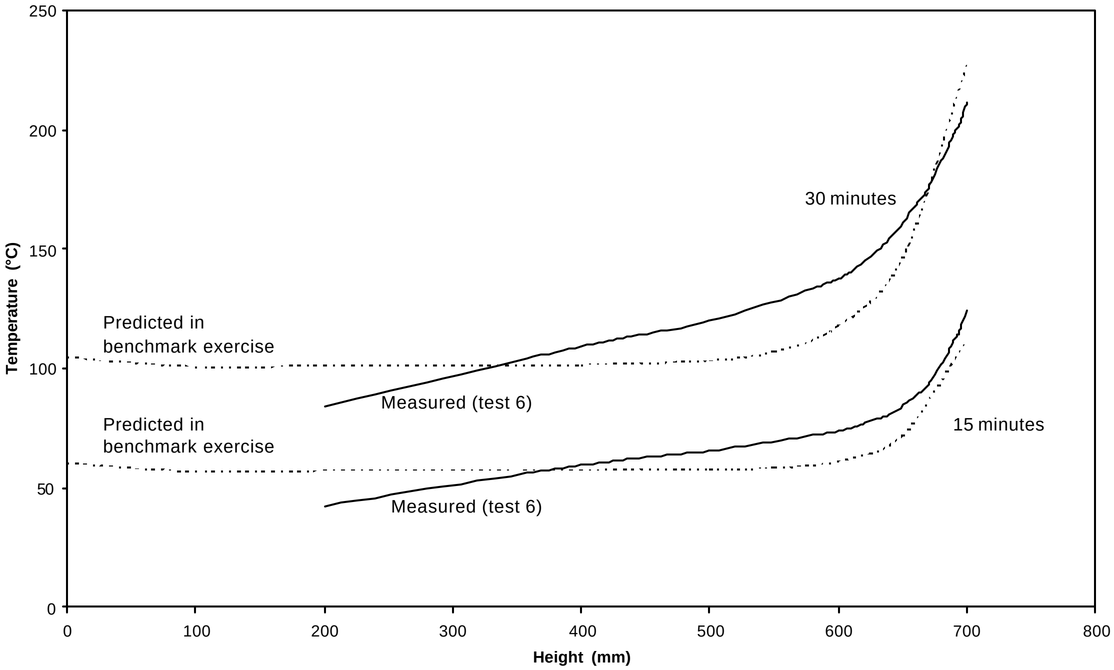

Figure 8 – The Water Temperature Profile in the Benchmark Test

results have therefore been used for comparison against the Rig data. A significant difference between the benchmark problem and the experimental test was the starting temperature. The TAU predicted results have therefore all been adjusted so that the apparent starting temperature is the same as that measured in the test.

The predicted and measured temperature of the water surface, as a function of time, is shown in Figure 7. Considering that the Transient Stratification Rig was not an exact replica of the benchmark exercise, and that convective flows in the water are not represented in the model, the agreement between the measured and predicted temperatures is very good, the predicted rise in water temperature being within 8% of that measured in the Rig.

The predicted and measured temperature profiles of the water down the centre-line of the vessel, at times of 15 and 30 minutes are shown in Figure 8. The temperature of the water is seen to be over-predicted near the bottom of the vessel and under-predicted near the centre of the vessel. This feature is probably due to the convective flow of the water not being represented in the TAU model. Near the water surface, however, where thermal stratification is greatest, the strong temperature gradient in the water will inhibit the convective flow of the water. If the main objective of a calculation is the determination of the water surface temperature, this data from the Transient Stratification Rig validates the use of the simple solid conduction model, with the water being modelled as a solid with an anisotropic conductivity.

CONCLUSIONS

A series of 12 tests have been carried out in the Transient Stratification Rig based upon the NEACRP thermal benchmark problem UK-4. The results show that under these conditions, with heating of the dry vessel walls above the water, strong thermal stratification occurs and high internal pressures are generated. The vapour pressure inside the vessel is demonstrated to be related to the temperature of the water surface.

The agreement with the calculated results of the benchmark problem is reasonably good, demonstrating that, by representing the water as a solid with an anisotropic conductivity, heat conduction codes can be used to adequately model thermal stratification in water-filled flasks.

REFERENCES

1. Glass R.E. et al, ‘Standard Thermal Problem Set’, Conf-890631. PATRAM ’89, 1, 275-282, 1989.

2. Johnson D. & Collier W.D, ‘TAU: A Computer Program for the Analysis of Temperature in Two- and Three-Dimensional Structures Using the UNCLE Finite Element Scheme’, AEA-FR-0010(R), 1990.