THERMAL-HYDRAULIC EXPERIMENTS ON THE TALL LBE TEST FACILITY

B.R. Sehgal, W.M. Ma, A. Karbojian
Royal Institute of Technology (KTH)
10044 Stockholm, Sweden

Abstract

In order to support ADS-related technologies, the thermal-hydraulic ADS lead-bismuth loop (TALL) was designed and constructed at KTH to investigate the heat transfer performance of different heat exchangers, and the thermal-hydraulic characteristics of natural and forced circulation flow under steady and transient conditions. The LBE loop is of full height and was scaled such that the prototypic (power/volume) ratio would represent the main components. So far, the forced convection and heat transfer of LBE through a straight tube heat exchanger and a U-tube heat exchanger have been accomplished and documented [1]. Transient experiments in the test facility are being conducted with reference to safety issues of ADS under the following conditions: a) startup and shutdown, b) loss of heat sink, c) loss of external driving head, d) heater trips, e) sudden change in power, and f) blockage in pipe. Preliminary tests were encouraging given the agreement of experimental data with RELAP5 analysis. More transient experiments and RELAP5 analysis will be performed in the future.

Introduction

Accelerator-driven systems (ADS) have been proposed for the transmutation of long-lived actinides in nuclear waste. Lead-bismuth eutectic (LBE) is likely to be a leading candidate for both coolant and target of ADS because LBE has exceptional chemical, thermo-physical and neutronic properties, which are well-suited for nuclear coolant and spallation target applications. In particular, LBE has a low melting temperature (~125 C) and a very high boiling temperature (~1 670 C). It is chemically inert, does not react violently with air and water, and its spallation can yield close to 30 neutrons per 1 GeV proton. However, LBE is not compatible with common steels used in nuclear installations, which therefore, requires specific protective measures. Due to its high atomic number, the understanding of LBE flow and heat transfer is necessary for the thermal-hydraulic design of an ADS.

Motivated by the increasing interest in transmutation of nuclear waste by LBE-cooled ADS worldwide, a great amount of R&D activities have been or are being performed to address the basic aspects of LBE technology. The European Union is one of the key players in this campaign, with 13 projects in the area of P&T of the EURATOM Fifth Framework Programme (FP5). The Royal Institute of Technology (KTH) is actively participating in the activities concerned with R&D on ADS technologies. We are partners in both the PDS-XADS and TECLA projects of FP5. The project of Technology, Materials and Thermal-hydraulics for Lead Alloys (TECLA) aims to validate the choice of LBE as the spallation material in the target and/or the coolant in a hybrid reactor. The key objective of TECLA is to investigate the corrosion phenomenon of the structural material with LBE and the thermal-hydraulic performance for LBE. We were involved in the medium-scale TECLA experiments on heat exchangers. According to the task, the thermal-hydraulic ADS lead-bismuth loop (TALL) was designed and constructed at KTH. Our guidelines for the design were not only to perform the experiments for heat exchangers, but also to establish an experimental platform for natural circulation and safety concerns in an LBE or lead-cooled reactor. As a result, the TALL facility was designed to perform transient experiments with reference to the safety issues of ADS.

The present paper focuses on a description of the TALL test facility, an overview of the investigation on heat exchangers and an introduction to ongoing transient experiments.

Description of the TALL test facility

TALL is a medium-scale facility designed to perform investigations on LBE flow and heat transfer with prototypic thermal-hydraulic conditions (as in the conceptual ADS design). The flow can be forced convection or natural circulation in character. TALL can also be used to study the performance of a conceptual design during representative accident scenarios. The first objective of TALL was to perform experiments for TECLA, i.e. to investigate the heat transfer performance of different heat exchangers. The second objective was to investigate the thermal-hydraulic characteristics of LBE natural circulation and forced circulation flow under steady and transient conditions.

Specifications

The specifications of TALL are set and modified to simulate prototypic thermal-hydraulic conditions of an ADS reactor, with well-conditioned flow and controllable power for thermal-hydraulic tests. The facility consists of a primary loop (LBE loop) and a secondary loop (oil loop). The LBE loop consists of sump tank, core tank, expansion tank, heat exchanger, EM pump, EM flowmeter, electric heaters and instrumentation. It is 6.8-m tall and the placement of heaters and heat exchangers allows natural convection flow as should occur in the prototypic vessel. Scaling is based on two considerations – resources and conceptual ADS designs. The LBE loop is of full height and has been scaled to prototypic (power/volume) ratio to represent all the components – their LBE volume, pressure drops, flow velocities and the heating rates corresponding to one tube of the chosen heat exchanger design. For the final design, partners and international collaborations provided the needed technological underpinning. The technical parameters are as follows.

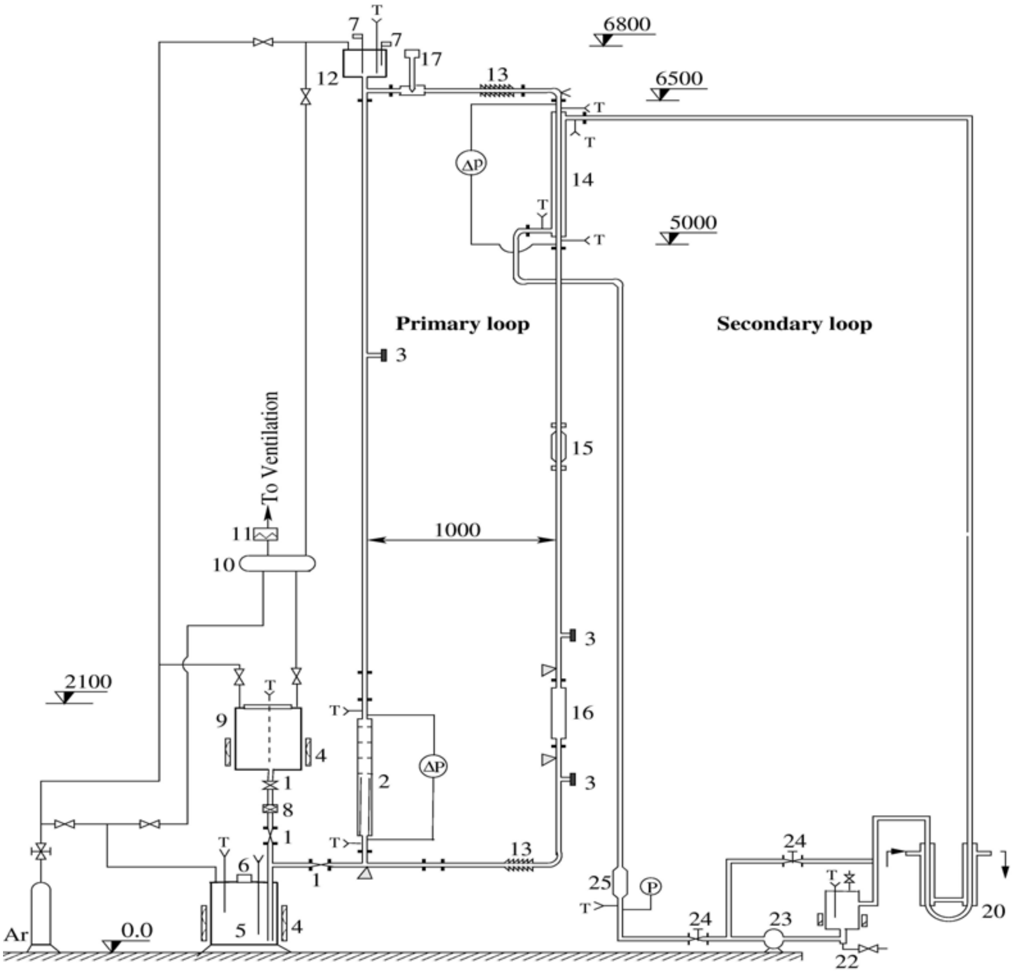
- All parts in contact with LBE are made of 316 or 316 L stainless steel.
- The overall height of the facility is 6.8 m.
- Total electric power is 55 kW and can be increased.
- LBE flow velocity is up to 3 m/s in the heat exchanger.
- LBE volume flow rate is up to 2.5 m^3/h.
- Maximum LBE temperature is up to 500°C.
- Maximum temperature difference along the heat exchanger is 150°C.
- The pressure at the top is ~1 bar and the bottom pressure is ~8 bar.
- Design natural convection velocity is »50 cm/s.
- The LBE is eutectic alloy with the composition of 45% Pb and 55% Bi in weight.
- LBE purity is higher than 99.5%.
- Oxygen level in LBE is measurable.
- The working fluid in secondary loop is glycerol $[C_3H_5(OH)_3]$ with a boiling point of 290°C.
- Configuration provides flexibility for different test sections.
- Data acquisition and control is provided.

Main components

TALL is composed of a primary loop and a secondary loop. The primary loop is a closed LBE loop consisting of a pump, flowmeter, oxygen meter, heaters, piping, heat exchangers and tanks. In addition, the facility has a data acquisition system, an oxygen measurement system, a cover gas system, a vacuum system and an exhaust system. The schema of the facility is depicted in Figure 1. The LBE operation and main components of the facility are described in detail in the text that follows.

For the first time only, LBE ingots are loaded into the melting tank, heated to 180°C and held 24 hours with argon flushing. Then, a scoop (fine mesh stainless steel) is used to clean the slag off the top of the LBE melt until the mirror surface shows and the molten LBE is transferred by drainage and argon pressure into the sump tank through the filter. During routine operation, the LBE is melted in the sump tank and pressurised to fill the loop. EM pump is used to circulate the molten LBE through the loop. After leaving the pump, the LBE flows through the core tank and is heated by immersion heaters to a specific temperature at the outlet, which is connected to a long vertical pipe. The LBE keeps travelling up the long vertical pipe to the expansion tank where the LBE turns to the oxygen sensor and then through the heat exchanger where the LBE's temperature is decreased to a certain value. The LBE leaves the heat exchanger and keeps flowing down through the EM flowmeter, which is placed on the long vertical pipe between the heat exchanger and the pump. The LBE finally returns to the pump.

Figure 1. Schema of the TALL test facility



Primary loop:
Piping––33.4mm O.D. and 27.8mm I.D.
Material––AISI 316 stainless steel
Working fluid –– LBE
Max flowrate –– 15 liters/min
Preheating of piping –– Rope heater

1–Valve for LBE
2–Core tank & heater (28kW)
3–Blind flange
4–Melting heater (6kW)
5–Sump tank for LBE
6–Observing window
7–Level sensor
8–Filter
9–Melting tank
10–Exhaust gas tank
11–HEPA filter
12–Expansion tank

Secondary loop:
Piping––26.7mm O.D. and 23.3mm I.D.
Piping material––carbon steel
Working fluid –– Glycerol
Max flowrate –– 260 liters/min
Preheating of piping –– Band heater

13–Expansion tube
14–LBE–oil heat exchenger
15–EM Flowmeter
16–EM Pump
17–Oxygen meter

20–Oil–water heat exchenger
21–heater (3kW)
22–Sump tank for oil
23–Oil pump
24–Valve for oil
25–Flowmeter for oil

Tanks

The melting tank is designed to melt commercial LBE ingots and to remove impurities. For preparation of the LBE melt, a round vessel is used. The melting tank was designed so that it can contain 150% of the loop's total volume with a certain free volume for cover gas plenum.

The sump tank collects the melted LBE from the melting tank before circulation. It has the same volume and diameter as the melting tank. It is placed under the loop so that it can collect and hold the LBE when the loop drains. An observation window is available on the top of the sump tank. During the operation, the LBE is melted in the sump tank and then transferred by cover gas pressure into the loop.

Two band heaters are employed to melt the LBE in each tank. The heaters are mounted around the outside surface of the vessel and are well-insulated. The LBE's temperature is controlled automatically by the controllable power supply system.

The highest located component of the loop is the expansion tank, which is used to collect the extra LBE from the loop due to heat expansion and to balance the pressure variation. All three tanks mentioned above are made of 316 stainless steel.

The core tank is one of the complicated components in the loop. It holds the immersion heaters that provide the main electric power supply. The core tank was scaled so that it could represent the reactor core corresponding to one tube of the heat exchanger, especially from the aspects of flow resistance and coolant inventory. Multi-hole plates are placed in the tank in order to increase the flow resistance. The number of the multi-hole plates can be changed in order to obtain the prototypic ratio of the core tank resistance to the loop's resistance. The immersion heaters are located in the lower part and the multi-hole plates are located in the upper part.

Heat exchanger

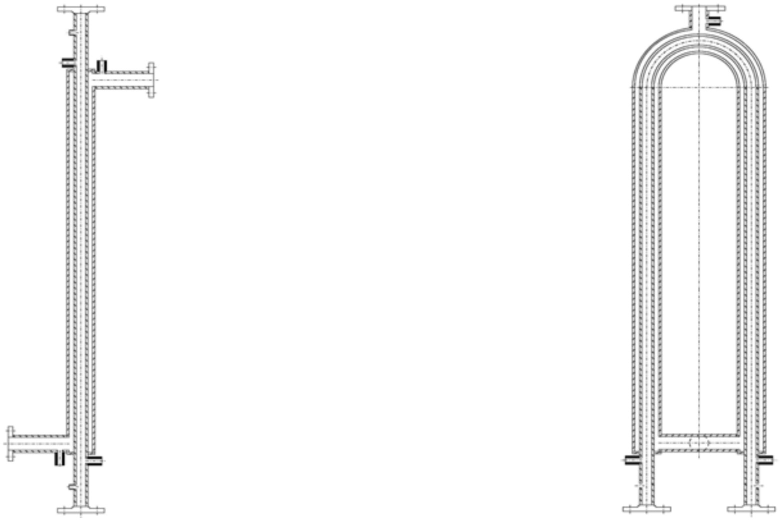
According to a sub-task of TECLA, the thermal-hydraulic performance of different types of heat exchangers will be investigated.

As shown in Figure 2, straight tube and U-tube heat exchangers were designed to perform the TECLA experiments.

Geometrical scaling is done in order to preserve relevant non-dimensional parameters (Re for forced circulation and Gr for natural convection) and is based on resources (such as laboratory condition, instrumentation and budget). As a result, single tube heat exchangers were employed. Both heat exchangers are composed of an inner tube and an outer duct, with the primary fluid (LBE) flowing in the inner tube and the secondary fluid (glycerol) flowing in the annulus. For the ease of fabrication, a square duct is chosen as the outer duct of the U-tube heat exchanger.

A 10-mm I.D. and 1.5-mm thick steel tube is used as the inner tube in both the heat exchangers. LBE velocities and Re numbers similar to those in the heat exchanger of the conceptual ADS design are easy to reach in the experiments. The effective lengths of both heat exchangers are one meter, which was decided after comprehensive consideration of the inlet/outlet temperature, heat removal capacity, heat flux and flow resistance.

Figure 2. Schema of the heat exchangers



(a) Straight tube

(b) U-tube

EM Pump

The electromagnetic (EM) pump provides the driving head for forced convection flow. The pump uses a system of rotating permanent magnets, which can withstand an LBE temperature of 300°C to 450°C as in our application. The LBE flows through the channel located in the gap between these magnets. An AC motor is employed to rotate the pump, on the shaft of which two magnetic disks are fixed.

The pump can develop 1.6 bar pressure at the flow rate of 0.6 L/s. Productivity of the pump is controlled by adjusting the rotation speed of the motor using a standard frequency converter.

Secondary loop

As shown in Figure 1, a secondary loop was designed to realise the heat transfer form LBE to an intermediate fluid, and finally to an oil-water heat exchanger. Glycerol [$C_3H_5(OH)_3$] was chosen as the working fluid (intermediate fluid) in the secondary loop because it has a high boiling point (290 C) and well known thermal properties. Glycerol’s boiling point is much higher than the melting point of LBE (125 C), which can also allow a higher operational temperature (‡ 125 C) so that solidification of LBE in the heat exchanger is avoided.

The secondary loop is an open circulation loop that consists of an oil pump, heat exchangers, sump tank, flowmeter, piping, valves and assorted temperature and pressure sensors. The oil pump is employed for the secondary loop to supply the flow driving head. During the operation, the glycerol leaves the oil sump tank due to suction of the pump. After leaving the pump, the flow is divided into two parts – one part returns to the sump tank via the bypass and the other part keeps flowing and turns up to a flowmeter where the flow rate is recorded. The bypass design is for easy control of the flow rate. The glycerol leaving the flowmeter travels through a long vertical pipe and arrives at the heat exchanger, where the glycerol’s temperature is increased due to heat received from the LBE. The glycerol leaves the heat exchanger, keeps flowing and turns down through the long vertical pipe and comes to another heat exchanger (oil-water heat exchanger) where the glycerol is cooled down by tap water and finally returns to the oil sump tank.

Instrumentation

The EM flowmeter is designed for measuring the flow rate of liquid LBE in a 316 stainless steel pipe with a diameter of 30 mm. The flowmeter consists of a sensor, an electronic block and a cable connecting the sensor with the electronic block.

The sensor is mounted vertically around the cold leg under the heat exchanger. The signal from the sensor is processed by an electronic block and the reading is shown on a PC monitor. The liquid LBE's temperature at the sensor can reach up to 400 C. The measuring range of the flowmeter varies from 0.01 L/s to 1.0 L/s.

In order to monitor the oxygen level in LBE, an oxygen measurement system is employed. The system consists of an oxygen sensor (from Los Alamos National Laboratory, USA) and a Keithley 6 514 programmable electrometer.

A Rosemount 3 051 differential pressure transmitter in combination with the1 199 diaphragm seal system is employed to measure the pressure drop of LBE flow.

An Omega FLMH-1 040 (AL)-HT high temperature oil flowmeter is used to measure the glycerol flow rate. Its temperature limit is up to 204 C. The flowmeter utilises a spring-and-piston type assembly, which enables it to be mounted in any position and gives immunity from changes in viscosity.

Thermocouples and pressure transducers are used to measure temperature and pressure, respectively. Electrical panels are available to control all operations of heaters, pumps and valves. A data acquisition system (DAS) is realised using National Instruments data input instrumentation and a computer program written in LabVIEW. The readings are performed through two SCXI-1 102 32-channel amplifiers and a 6 035E analogue input DAQ card.

Tests on the heat exchangers

The facility came into operation in September 2003. Tests on a straight tube and a U-tube heat exchanger have since been conducted. The ranges of the main thermal-hydraulic parameters of LBE in a heat exchanger are: inlet temperature from 230 C to 450 C, temperature drop from 20 C to 100 C, and velocity from 0.5 m/s to 2.5 m/s. The pressure drop and heat transfer characteristics were obtained for the straight tube heat exchanger and the U-tube heat exchanger, respectively.

Figure 3 shows the variation of the pressure drop with the Reynolds number for the two tested heat exchangers. It is obvious that the pressure drop of the LBE flow through the U-tube is larger than that of the straight tube.

For LBE flow in a straight tube, it appears that the present measured values are on average 15% higher than those from the following Techo, *et al.*, correlation, which is for fully developed turbulent flow and smooth surface conditions.

$$\frac{1}{\sqrt{f}} = 1.7372 \ln \frac{\mathrm{Re}}{1.964\,\mathrm{Re} - 3.8215} \tag{1}$$

For a commercial stainless steel tube, if roughness may be chosen as 0.018 mm, the pressure drop calculated by the following Moody correlation will be in reasonable agreement with experimental data.

$$f = 1.375 \cdot 10^{-3} \left[1 + 21.544 \left(\frac{2e}{d} + \frac{100}{\mathrm{Re}} \right)^{1/3} \right] \tag{2}$$

For both heat exchangers, the overall heat transfer coefficient increases with the increasing LBE and glycerol flow rate (illustrated in Figures 4 and 5), but the glycerol flow rate has a more significant effect. Furthermore, the overall heat transfer coefficient of the U-tube heat exchanger is higher than that obtained in the straight tube heat exchanger under the same conditions. More details of tests on heat exchangers are documented in Ref. [1].

Figure 3. Pressure drops of LBE flow through the heat exchangers

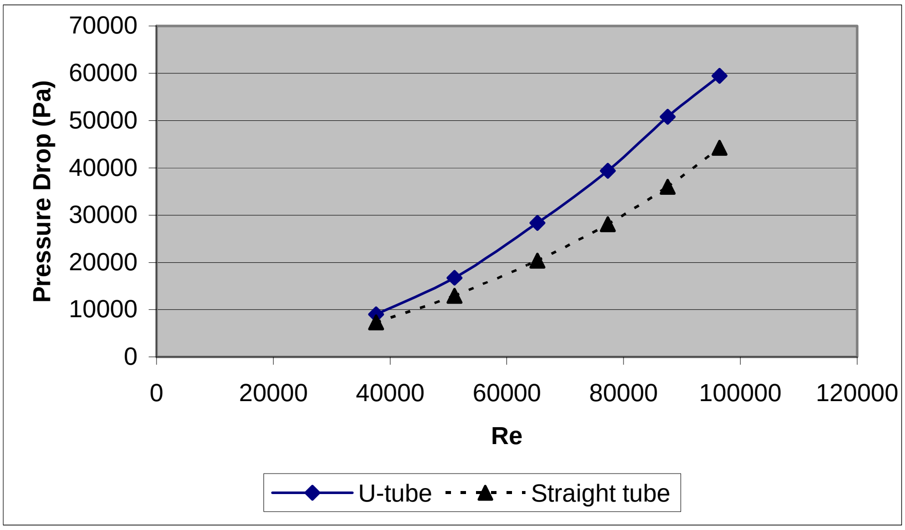


Figure 4. Effect of the glycerol flow rate on heat transfer

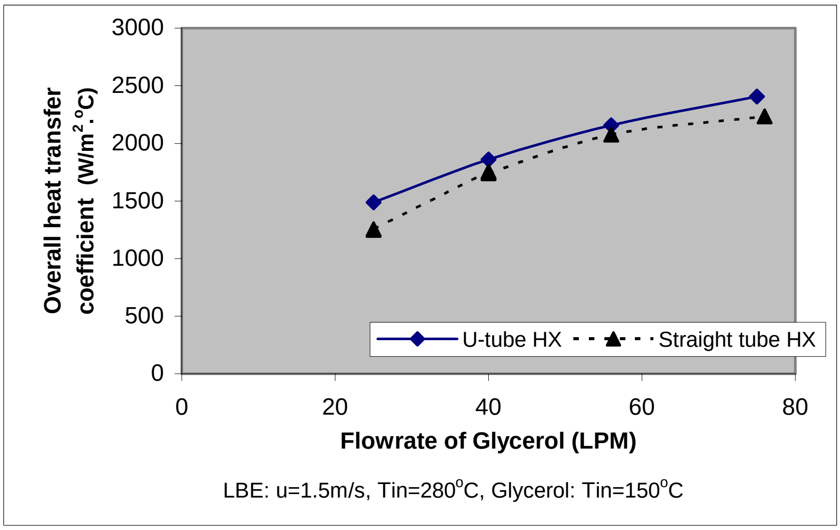
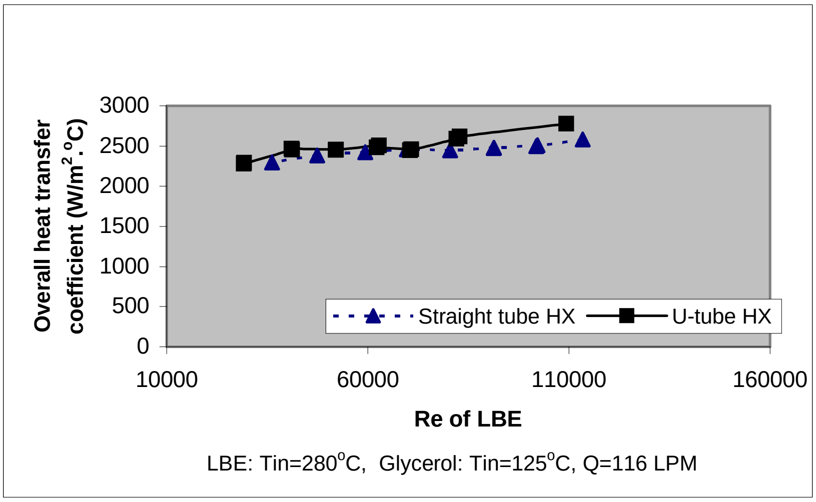


Figure 5. Effect of the LBE flow rate on heat transfer



Transient tests

Transient experiments with reference to safety issues of ADS were started in May 2004. While simulating decay heat in the core tank, the temperature and flow rate characteristics will be measured during the following transients:

a) Startup or shutdown of the facility.

b) Loss of heat sink (switch off pump in secondary loop).

c) Loss of external driving head (switch off pump in primary loop) – completely passive mode of LBE loop operation.

d) Switch on and off the heater to simulate accelerator trips.

e) Blockage in pipes.

f) Sudden increase or decrease in power.

It was deemed important to find a way to measure low velocity during LOF transients. As a result, the flowmeter was recalibrated and the correlation between flow rate and pressure drop through the heat exchanger was obtained, which provides a sound basis to monitor the flow change during the transients.

Based on improved measurement, a loss of flow transient is shown in Figure 6. The transient was stopped at 628 seconds since the temperature was reaching the limit. The variations of flow rate and temperature were very similar to the RELAP5 calculations as shown in Figure 7, which provides an encouraging perspective on the experiment and calculations, though they started from different initial conditions. If a new model of an EM pump is taken into account and the same initial conditions are used, we believe that the experiment and calculations will show good quantitative comparison.

The transient experiments are just at the beginning. More experiments will be performed during the next few months. A RELAP5 analysis will also be performed.

Figure 6. The transient of loss of external driving head in the primary loop

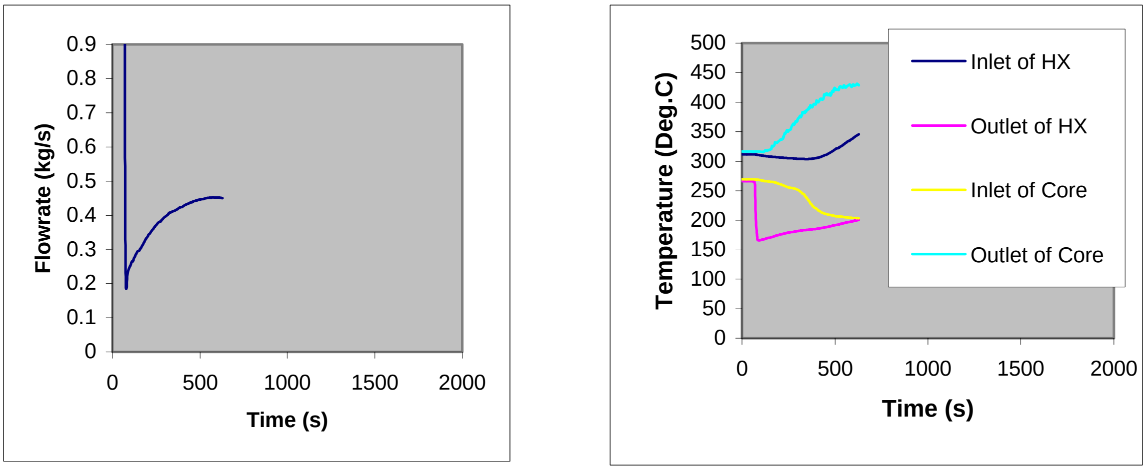
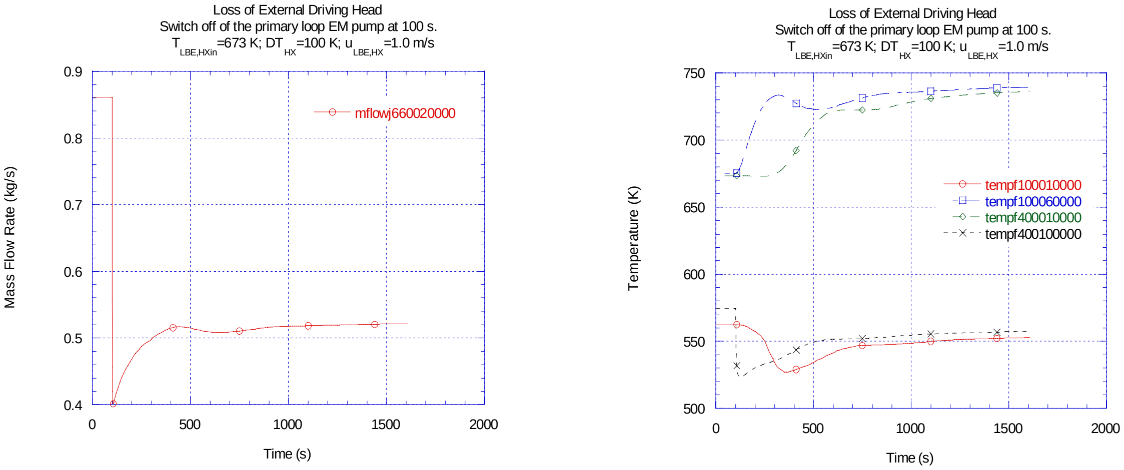


Figure 7. Calculation of the transient of loss of external driving head in the primary loop



Concluding remarks

The TALL facility was designed to investigate transients with reference to safety issues as well as the thermal-hydraulic performance of heat exchangers in a conceptual ADS subcritical reactor design. Thus, it is a multi-purpose test platform. The facility came into operation in September 2003. So far, investigations have been performed on two different heat exchangers, one with a straight tube and one with a U-tube. Transient experiments addressing safety issues of the ADS are on the way. More data on transients and natural circulation will be obtained during the next several months. According to test progress, the main conclusions are as follows:

- The loop is well-controlled and the thermal-hydraulic conditions can be adjusted properly.
- The operational parameters, e.g. LBE flow rate and temperature level, meet design requirements.
- The LBE inlet temperatures of the heat exchangers are up to 450 C, with the outlet temperature of the core tank up to 500 C.

- Pressure drop through the straight tube appears to be higher than that calculated via the Techo, *et al*., correlation (1) for a smooth tube, but in good agreement with that calculated via the Moody correlation (2), which takes into account the effect of surface roughness.

- The heat transfer coefficient of secondary (glycerol) flow is much smaller than that of primary (LBE) flow, and hence dominates the determination of the overall heat transfer coefficient.

- In general, the U-tube heat exchanger has a better heat transfer performance than the straight tube heat exchanger, especially for secondary flow. In fact, the heat transfer resistance is very low for primary flow, thus any heat transfer enhancement design should be put on the secondary side.

- Preliminary tests are encouraging for the agreement of experimental data with RELAP5 analysis.

- More experiments, data check and analysis will be carried out.

Acknowledgements

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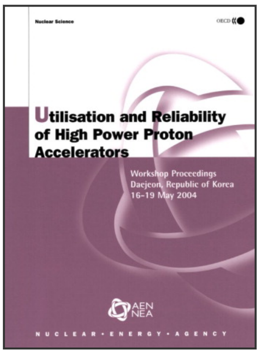

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