Available online at www.sciencedirect.com
ScienceDirect
Journal of Nuclear Materials 376 (2008) 401–404
journal of nuclear materials
www.elsevier.com/locate/jnucmat

European research on HLM thermal-hydraulics for ADS applications

F. Roelofs [a,*], B. de Jager [a], A. Class [b], H. Jeanmart [c], P. Schuurmans [d], A. Ciampichetti [e], G. Gerbeth [f], R. Stieglitz [b], C. Fazio [b]

[a] NRG, Westerduinweg 3, 1755 LE Petten, Netherlands
[b] FZK, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[c] UCL, Louvain la Neuve, Belgium
[d] SCK · CEN, Boeretang 200, B-2400 Mol, Belgium
[e] ENEA, 40032 Camugnano, Brasimone, Italy
[f] FZD, P.O. Box 510119, 01314 Dresden, Germany

Abstract

The objective of the European 6th framework project EUROTRANS is to demonstrate the technical feasibility of transmutation of high level nuclear waste using accelerator driven systems. Within this objective the design of a European experimental ADS should demonstrate the technical feasibilities to transmute a sizeable amount of waste and to operate an ADS safely. This ADS will be a subcritical reactor system having liquid lead–bismuth eutectic as coolant. The liquid lead–bismuth eutectic is also intended to serve as target material for the spallation reaction which forms a crucial part to the subcritical reactor core. Since lead–bismuth eutectic is used as core coolant and spallation material, knowledge of its thermal hydraulic behaviour is essential. Within the DEMETRA domain of the EUROTRANS project, basic thermal hydraulic studies in order to support the design and safety analysis of XT-ADS components and the development of measurement techniques have been started.

1. Introduction

The objective of the European 6th framework project EUROTRANS [1], sponsored by the European Commission, is to demonstrate the technical feasibility of transmutation of high level nuclear waste using accelerator driven systems (ADS). Within this objective, the design of a European experimental ADS (XT-ADS) should demonstrate the technical feasibilities to transmute a sizeable amount of waste and to operate an ADS safely. Besides that, the conceptual design of an European facility for industrial transmutation (EFIT) is foreseen. Both systems will be subcritical reactors having liquid lead–bismuth eutectic (LBE) and lead as coolant, respectively. This liquid metal is also intended to serve as target material for the spallation reaction which forms a crucial part to the subcritical reactor core. Since liquid metal is used as core coolant and spallation material, knowledge of the thermal hydraulic behaviour of liquid metal is essential. Due to the functional similarity between the XT-ADS and the so-called MYRRHA Draft 2 concept, as developed by the Belgian nuclear research institute SCK · CEN [2], the MYRRHA Draft 2 design was chosen as a starting point for the design of the XT-ADS.

Within the DEMETRA domain [3] of the EUROTRANS project, basic thermal hydraulic studies in order to support the design and safety analysis of XT-ADS components and the development of measurement techniques have been started. In particular, the work focuses on:

– characterisation of the free surface flow for the windowless spallation target design;
– the interaction of LBE with water as secondary coolant;
– the development of measurement techniques for heavy liquid metal (HLM) flows.

* Corresponding author. Tel.: +31 224 568236; fax: +31 224 568490.
E-mail address: roelofs@nrg.eu (F. Roelofs).

0022-3115/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2008.02.014

The work on the characterisation of the free surface flow for the windowless spallation target is directly linked to the design of the windowless spallation target for the XT-ADS within the DESIGN domain of the EUROTRANS project. The interaction between LBE and water as secondary coolant has an impact on the design selection and safety considerations of the ADS heat exchanger. These studies are also used to prepare a large scale integral experiment which is foreseen within the DEMETRA domain in the CIRCE facility at ENEA [3]. Since a large number of European lead/LBE experimental facilities are involved, this work is also closely linked to the European Commission Integrated Infrastructure Initiative VELLA (Virtual European Lead LAboratory [4]). Furthermore, as the developed heavy liquid metal (HLM) technologies are also applicable to a lead cooled fast reactor (LFR), this work is related to the European Commission Specific Targeted Research Project ELSY (European lead-cooled system [5]).

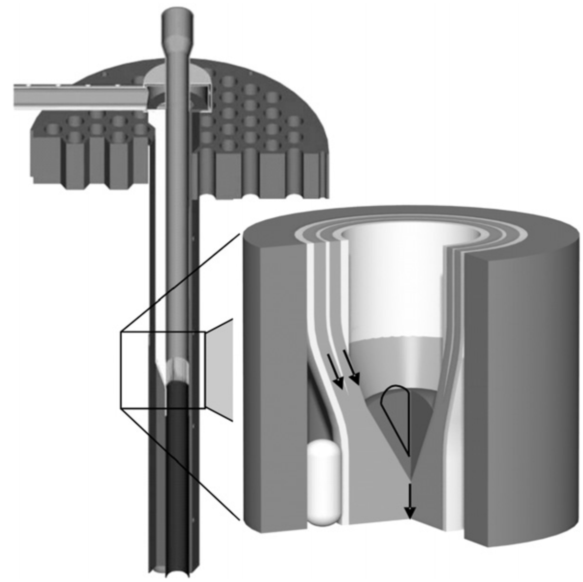

Fig. 1. Schematic view of the vertical confluent flow design of the MYRRHA Draft 2 windowless spallation target.

2. Characterisation of the free surface flow in the windowless target

2.1. Windowless target

As outlined before, the MYRRHA Draft 2 concept has served as starting point for the design of the XT-ADS. Therefore, also the design of the spallation target of the XT-ADS is based on the windowless spallation target design of the MYRRHA Draft 2 concept [6]. The limited space available for the external neutron source in the core of the XT-ADS and the high proton current, lead to very high proton beam densities. At present, no structural material is expected to withstand such extreme conditions at the operational temperatures foreseen for the XT-ADS during a reasonable lifetime of at least one year. Therefore, an LBE windowless spallation target is chosen in which there is direct contact between the proton beam from the accelerator and an LBE free surface flow. This results in a challenging task for the design of the spallation target. The design of the target nozzle has to be such that an LBE free surface flow is created within the geometrical constraints imposed by the compact subcritical core. Furthermore, it should remove the heat deposited by the proton beam adequately. Besides that, the design has to be compatible with the vacuum requirements of the beam transport system. These constraints lead to a design of the windowless spallation target with a vertical confluent flow as presented in Fig. 1.

2.2. Numerical model development

Since no experiment can demonstrate the ability to transport the deposited heat in a windowless spallation target adequately, validated numerical methods are required. For this purpose, computational fluid dynamics (CFD) simulation methods are the most appropriate. CFD methods are capable of capturing the specific three-dimensional local effects of the LBE free surface including the heat deposition. This requires sufficiently accurate free surface modelling, predicting a unique (sharp) interface between LBE and beam vacuum in combination with adequate turbulence modelling. In the European 5th framework project ASCHLIM [7], it was demonstrated that sufficiently accurate CFD modelling of such free surface targets was not possible with the state-of-the-art methods available at that time. This is confirmed in Refs. [8–10]. Within the EUROTRANS project, the development of CFD methods for the simulation of the removal of deposited heat in the LBE windowless target has been envisaged. Different methods are assessed by NRG, FZK, and AAA and qualitatively compared to existing real size water flow experiments performed at UCL [11], mercury experiments performed at IPUL [11], and LBE flow experiments at FZK [12]. The following numerical methods are assessed by the different partners:

- volume of fluid (VOF) method;
- VOF method combined with cavitation module;
- Euler–Euler method;
- moving mesh algorithm (MMA) method.

First assessments have been made for the isothermal situation [13,14], i.e. without taking into account the heat deposition of the proton beam. The results highlight that the application of the VOF model in combination with the cavitation module in STAR-CD and the application of the Euler–Euler model in CFX10 are very promising, although both models still require improvements. Furthermore, it is concluded that the VOF model without cavitation model does not lead to realistic results. The MMA method is still under evaluation. First results are expected by the end of 2007.

2.3. Experimental campaign

An experimental campaign has started for the improvement and validation of the developed numerical models. This campaign foresees experiments in a water loop of UCL and in a lead–bismuth loop in the KALLA laboratory of FZK. Preliminary experiments in the water loop at UCL have already been performed using the MYRRHA Draft 2 spallation target design assessing the influence of adding a mild swirl to the annular feeder flow on the behaviour of the free surface. These experiments confirm the conclusions obtained through numerical simulations performed by FZK and NRG. In particular, the addition of a swirl of about 10% leads to an unacceptable vacuum core vortex in the central downcomer of the spallation loop.

2.4. Numerical support to experiments

The experimental campaign is supported by numerical simulations. Apart from the swirl simulations mentioned before, the so-called target header was designed and optimised using CFD simulations. The target header is the device where the horizontal feeder flow is directed into the vertical annular feeder nozzle. The objective was to obtain a uniformly distributed mass flow rate in this annular feeder. Using the CFD-code STAR-CD, the Italian institute CRS4 designed and optimised the target header.

3. LBE–water interaction

3.1. Experimental campaign

The XT-ADS design foresees the presence of LBE–water heat exchangers or steam generator modules placed inside the main vessel. This allows direct contact between LBE as primary coolant and water as secondary coolant in the case of a tube rupture. Since the probability of a tube rupture cannot be neglected, the consequences of such an accident have to be assessed. The experimental campaigns, which are performed in the LIFUS-5 facility of ENEA in Italy, aim at assessing the physical effects and possible consequences related to the interaction of LBE and water in representative conditions. For this purpose, a steam generator mock-up is placed in a reaction vessel (S1) filled with LBE. Water is injected into the LBE by means of an injection device that can be placed at different heights below the steam generator mock-up or among its tubes. Fast pressure transducers and thermocouples at various locations register the pressure and temperature evolution during the experiment. A first experimental test aimed at obtaining first data concerning LBE–water interaction, has been successfully performed injecting pressurised water at 70 bar in the reaction vessel of LIFUS-5 containing LBE at 350 °C [15]. For the applied conditions, a pressure increase of about 10 bar above the injection pressure (70 bar) was observed and no steam explosion occurred.

3.2. Numerical program

The experimental data are also used for the validation of the SIMMER III code by ENEA/UNIPI and CEA. The SIMMER III code is a fluid dynamics code coupled with a space–time and energy-dependent neutron transport kinetics model [16]. First simulations with a two-dimensional model performed by ENEA/UNIPI show a reasonable comparison between the simulation results and the experimental data. The pressure increase above the injection pressure was predicted correctly. However, the exact value of the pressure peak and the time evolution give reason for improvement of the numerical model by extending the model to three dimensions and by a more accurate geometrical representation of the steam generator mock-up.

4. Development of measurement techniques

Measurement techniques are developed for thermal-hydraulics experiments and for operational techniques in the XT-ADS and EFIT reactors. These techniques are tested within the laboratories of FZD, FZK, and SCK · CEN. The focus is on local velocity meters, integral contactless flow meters, and free surface level sensors. Two types of flow meters and two types of free surface level sensors will be described hereafter.

4.1. Flow meters

Contactless electromagnetic flow meters (EMFM) based on different principles are developed in parallel. One EMFM is based on the principle of phase shift and is developed by FZD [17]. This EMFM is validated against a commercial flow rate sensor as well as local velocity measurements using ultra doppler velocimetry (UDV) in a GaInSn-loop at FZD. Furthermore, the EMFM measuring device is made resistant against temperatures up to 800 °C. Two devices are developed which are ready for further testing in existing liquid metal loops. One device is able to measure flow rates in channels up to 85 mm. The other device can be attached to a channel using a clamp. The latter system can be used in channels up to 34 mm and temperatures up to 800 °C.

Another EMFM under development by FZK is based on the principle of dragging magnetic field lines. This flow meter is able to detect the flow direction. Besides that, a self calibrating method is developed for this type of flow meter. First successful tests have been performed in the KALLA laboratory at FZK.

4.2. Free surface measuring techniques

Free surface measuring techniques are required for experimental as well as operational purposes. Concerning the experimental purposes, the measuring technique requires accurate measurement of the free surface shape and position. For this purpose, FZK is developing a non-invasive detection method based on the double layer projection technique (DLP). The proof of principle is demonstrated on a static and a rotating mirror. Further validation is foreseen on a circular hydraulic jump experiment [18].

Concerning the operational purposes, the measuring technique has to fulfil different requirements. During operation of the XT-ADS, accurate and frequent knowledge about the position of the free surface is required for reactor and beam control. This leads, in addition to the not readily accessible location of the free surface in the reactor core, to very stringent requirements for the technique under development. In particular, the distance between sensor and surface is about 10 m, the accuracy should be lower than 1 mm, and the measuring frequency should be about 1 kHz. SCK · CEN has selected a time of flight (TOF) technique for this purpose.

5. Summary

This paper summarises the ongoing work performed within the framework of the 'advanced thermal-hydraulics and measurement techniques' workpackage of the DEMETRA domain of the European integrated project EUROTRANS. This work focuses on the characterisation of the free surface flow for the windowless spallation target design, the interaction of LBE with water as secondary coolant, and the development of measurement techniques for heavy liquid metal (HLM) flows. Main achievements are:

– development of numerical methods for the simulation of the isothermal windowless target;
– determination of the influence of adding a mild swirl in a windowless target water loop;
– performance of a first LBE–water interaction experiment which shows a pressure increase above the injection pressure and no occurence of a steam explosion;
– reasonable results for the simulation of the first test concerning the LBE–water interaction using the SIMMER III code with a two-dimensional domain;
– development of EMFM devices for the contactless measuring of HLM flow rates;
– development of DLP free surface measuring technique for the determination of free surface shape and position in experiments.

Acknowledgments

The authors would like to thank all participants (AAA, ANS, CEA, CRS4, ENEA, FZD, FZK, NRG, SCK · CEN, and UCL) involved in the workpackage 'advanced thermal-hydraulics and measurement techniques' of the EUROTRANS project. The work described in this paper was carried out in and supported by the FP6 EC Integrated Project EUROTRANS No. FI6W-CT-2004- 516520.

References

[1] J. Knebel et al., Integrated Project EUROpean Research Programme for the TRANSmutation of High Level Nuclear Waste in an Accelerator Driven System, 2005. EUROTRANS, EC Project No. FI6W-CT-2004-516520.
[2] H. Aït Abderrahim et al., MYRRHA Pre-Design File – Draft 2, SCK-CEN report R-4234, Mol, Belgium, 2005.
[3] C. Fazio, A. Alamo, J. Henry, A. Almazouzi, D. Gomez-Briceno, L. Soler, J.-B. Vogt, F. Groeschel, F. Roelofs, P. Turroni, R. Stieglitz, J. Knebel, European Research on Heavy Liquid Metal Technology for Advanced Reactor Systems, 15th PBNC, Sydney, Australia, 2006.
[4] G. Benamati et al., Virtual European Lead Laboratory, VELLA, 2006, EC Project No. FI6W-036469.
[5] G. Locatelli et al., Specific Targeted Project European Lead-cooled System, ELSY, 2006, EC Project No. FI6W-036439.
[6] P. Schuurmans, K. van Tichelen, M. Dierckx, H. Aït Abderrahim, A. Guertin, T. Kirchner, A. Cadiou, J.M. Buhour, R. Stieglitz, D. Coors, L. Mansani, F. Roelofs, Design and Supporting R&D of the XT-ADS Spallation Target.IEM on Actinide and Fission Product P&T, Nîmes, France, 2006.
[7] Arien et al., Assessment of Computational Fluid Dynamic Codes for Heavy Liquid Metals – ASCHLIM, 2004, EC-Con. FIKW-CT-2001-80121-Final Rep.
[8] K. van Tichelen, P. Kupschus, H. Aït Abderrahim, J.-M. Seynhaeve, G. Winckelmans, H. Jeanmart, MYRRHA: Design of a Windowless Spallation Target for a Prototype Accelerator Driven System, ICENES-2000, Petten, Netherlands, 2000.
[9] K. van Tichelen, P. Kupschus, F. Roelofs, M. Dierckx, H. Aït Abderrahim, Free Surface Fluid Dynamics Code Adaptation by Experimental Evidence for the MYRRHA Spallaton Target. IAEA TM on Theoretical and ExpStudies of HLM Thermal Hydraulics, Karlsruhe, Germany, 2003.
[10] C. Fazio, A. Alamo, A. Almazouzi, D. Gomez-Briceno, F. Gröschel, F. Roelofs, P. Turroni, J. Knebel, Assessment of Reference Structural Materials, Heavy Liquid Metals, and Thermal-hydraulics for European Waste Transmutation ADS, Global 2005, Tsukuba, Japan, 2005.
[11] K. van Tichelen, P. Kupschus, H. Aït Abderrahim, A. Klujkin, E. Platacis, MYRRHA: Design and Verification Experiments for the Windowless Spallation Target of the ADS Prototype MYRRHA, AccApp01, Reno, Nevada, USA, 2001.
[12] T. Schulenberg, X. Cheng, R. Stieglitz, Thermal-hydraulics of Lead–bismuth for Accelerator Driven Systems, NURETH11, Avignon, France, 2005.
[13] A. Batta, A. Class, Numerical Investigations on Geometrical Designs of the Windowless XT ADS Spallation Target, ICAPP07, Nice, France, 2007.
[14] F. Roelofs, N.B. Siccama, S. Willemsen, Development of an Euler–Euler Two-Phase Model for Application in the Windowless XT-ADS Spallation Target Design, ICAPP07, Nice, France, 2007.
[15] A. Ciampichetti, LBE/water interaction in sub-critical reactors: first experimental and modelling results, IV Workshop on Materials and for HLM-cooled Reactors and Related Technologies, Rome, Italy, 2007.
[16] Y. Tobita, SA. Kondo, H. Yamano, K. Morita, W. Maschek, P. Coste, T. Cadiou, Nucl. Technol. 153 (3) (2006) 245.
[17] J. Priede, D. Buchenau, G. Gerbeth, A contact-less electromagnetic induction flowmeter based on phase shift measurements, EPM, Sendai, 23–27 October, 2006, Proceedings, p. 735.
[18] M. Hillenbrand, T. Schmidt, R. Stieglitz, A. Class, H. Piecha, G.P. Neitzel, Measurement and Computation of Free Surface Flows of Liquid MetalsJahrestagung, Karlsruhe, Germany, 2007.