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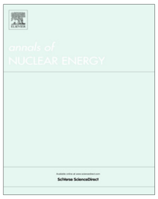

An experimental test facility to support development of the fluoride-salt-cooled high-temperature reactor

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ABSTRACT

The need for high-temperature (greater than 600 °C) energy transport systems is significantly increasing as the world strives to improve energy efficiency and develop alternatives to petroleum-based fuels. Liquid fluoride salts are one of the few energy transport fluids that have the capability of operating at high temperatures in combination with low system pressures. The fluoride-salt-cooled high-temperature reactor design uses fluoride salt to remove core heat and interface with a power conversion system. Although a significant amount of experimentation has been performed with these salts, specific aspects of this reactor concept will require experimental confirmation during the development process.

The experimental facility described here has been constructed to support the development of the fluoride-salt-cooled high-temperature reactor concept. The facility is capable of operating at up to 700 °C and incorporates a centrifugal pump to circulate FLiNaK salt through a removable test section. A unique inductive heating technique is used to apply heat to the test section, allowing heat transfer testing to be performed. An air-cooled heat exchanger removes added heat. Supporting loop infrastructure includes a pressure control system, a trace heating system, and a complement of instrumentation to measure salt flow, temperatures, and pressures around the loop.

The initial experiment is aimed at measuring fluoride-salt heat transfer inside a heated pebble bed similar to that used for the core of the pebble-bed advanced high-temperature reactor.

This paper describes the details of the loop design, auxiliary systems used to support the facility, inductive heating system, and facility capabilities.

1. Introduction

Effective high-temperature thermal energy transport at temperatures greater than 600 °C can impact a variety of energy technologies by improving system efficiencies and reducing system size, resulting in reduced capital and operating costs of energy conversion and transport systems. It is one of the key advances necessary for efficient hydrogen production and could potentially enhance efficiencies of high-temperature solar systems. Today there are no standard, commercially available fluids for high-performance heat transfer above 600 °C. High pressures associated with water and gaseous coolants (such as helium) at elevated temperatures impose limiting design conditions for the materials in most energy systems. Liquid salts offer high-temperature capabilities at low vapor pressures, good heat transport properties, and reasonable costs and are therefore leading candidate fluids for next-generation energy production. Liquid-fluoride-salt-cooled, graphite-moderated reactors, referred to as fluoride-salt high-temperature reactors (FHRs), are specifically designed to exploit the excellent heat transfer properties of liquid fluoride salts while maximizing thermal efficiency and minimizing cost. The FHR's outstanding heat transfer properties, combined with its fully passive safety, make this reactor the most technologically desirable nuclear power reactor class for next-generation energy production.

Multiple FHR designs are presently being considered. These range from the pebble-bed advanced high-temperature reactor (PB-AHTR) design originally developed by the University of California-Berkeley (UC-Berkeley) Bardet et al. (2009) and Brook (2010) to the small advanced high-temperature reactor (Greene, 2010) and large-scale advanced high-temperature reactor designs being developed at Oak Ridge National Laboratory (Ingersoll et al., 2004; Varma et al., 2012). The value of high-temperature, molten-salt-cooled and molten-salt-fueled reactors is also internationally recognized, and the Czech Republic (Hron et al., 2009) France, India, and China (Dai, 2013) all have liquid salt research under way, with China planning on completing an FHR test reactor in the 2017 timeframe. Organizations are also studying molten-salt-fueled concepts. The molten salt fast reactor (MSFR) is presently being developed by the Euratom Evaluation and Viability of Liquid Fuel

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Fast Reactor System Project (also known as EVOL) (Merle-Lucotte et al., 2011) with the objective of developing a design for an MSFR by 2014, while the Chinese Academy of Science is also pursuing a salt-fueled reactor design (Dai, 2013).

The initial experiment planned for the liquid salt test loop will demonstrate the heat transfer performance of liquid fluoride salt in a fixed pebble bed. The test pebble bed resembles that proposed for the 2008 design of the PB-AHTR and is similar to that proposed for the Chinese pebble bed thorium molten salt reactor [TMSR(SF)]. The 2008 core design of the PB-AHTR features multiple 20 cm diameter, 3.2 m long fuel channels with 3 cm diameter graphite-based fuel pebbles slowly circulating up through the core. The Chinese TMSR(SF) uses 6 cm diameter pebbles in a 140 cm outer diameter annular core that is 140 cm long. For both designs the fuel pebbles consist of triso-type fuel particles encased within a graphite matrix similar to those used in the pebble bed gas-cooled reactor design (Koster et al., 2004). Molten salt coolant, a eutectic of lithium fluoride and beryllium fluoride (FLiBe) flows upward through the pebble bed and is used to remove heat generated in the reactor core and supply it to a power conversion system. The PB-AHTR design is discussed in detail in Bardet et al. (2009) and shown schematically in Fig. 1. The TMSR(SF) is discussed in Dai (2013).

The experimental facility being developed is a forced convection salt loop designed to provide prototypic fluid conditions to a removable test section. It uses a unique inductive heating technique to provide volumetric pebble heating that is prototypic of nuclear heating. The facility design is also sufficiently versatile to allow a variety of other experimentation to be performed in the future, serving as the centerpiece of an FHR component test facility. The facility can accommodate testing of scaled reactor components or subcomponents such as flow diodes, salt-to-salt heat exchangers, and improved pump designs as well as testing of refueling equipment, high-temperature instrumentation, and other reactor core designs.

The initial test program is designed to evaluate the heat transfer in a static pebble bed simulating the core region of a pebble-bed FHR. The inductive heating provides prototypic heating of the pebbles. An extensive amount of work has been conducted to examine the performance of packed and fluidized beds in support of the chemical and petroleum industries, and entire texts are devoted to this subject (Wakao, 1982; Kolev, 2006). Packed beds are used to enhance both mass and heat transfer performance, and specific packing designs have been developed over the years to optimize these characteristics. In most packed bed systems used to improve heat transfer performance, heat is added externally, and the packing is used to augment heat transfer in the channel. The existing body of literature includes studies investigating radiative as well as convective transport within the bed (Yee and Kamiuto, 2005; Singh and Kaviany, 1992) the influence of the wall on geometrical packing (Ridgway and Tarbuck, 1968; McWhirter et al., 1997), and details of the turbulence within the bed (Travkin et al., 1999; Pedras and de Lemos, 2000), as well as other phenomena. A unique feature of pebble-fueled reactor systems is that heat is generated within the pebbles themselves, and the heat transfer from the pebble to the molten salt dictates the fuel temperature, ultimately establishing reactor operating limits.

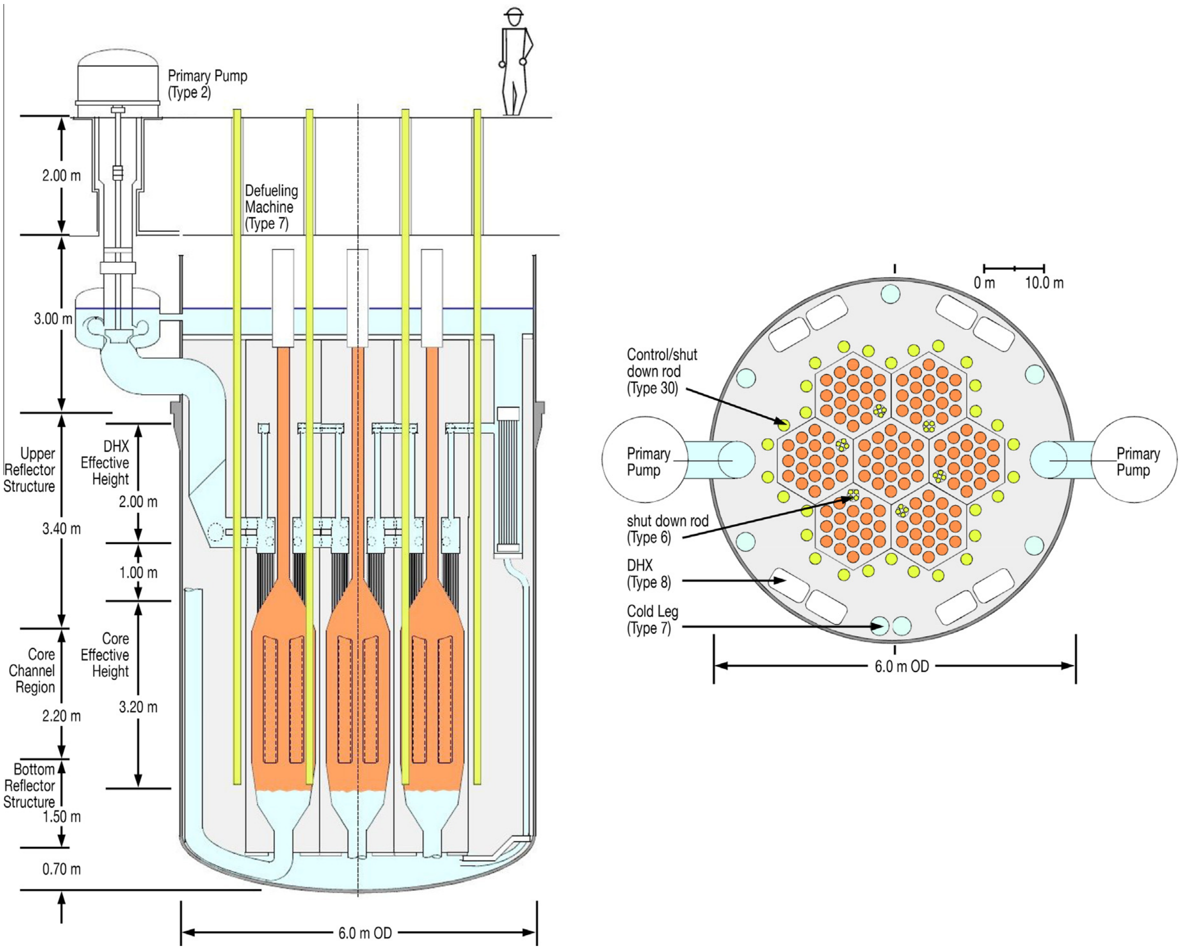

Fig. 1. PB-AHTR concept (drawing taken from reference Bardet et al. (2009)).