

Thermodynamic calculations of a two-phase thermosyphon loop for cold neutron sources



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ABSTRACT

A new method is described for thermodynamic calculations of a two-phase thermosyphon loop based on a one-dimensional finite element division, where each time-step is split up in a change of enthalpy and a change in entropy. The method enables the investigation of process responses for a cooling loop from room temperature down to cryogenic temperatures. The method is applied for the simulation of two distinct thermosyphon loops: a two-phase deuterium and a two-phase hydrogen thermosyphon loop. The simulated process responses are compared to measurements on these loops. The comparisons show that the method can be used to optimize the design of such loops with respect to performance and resulting void fractions.

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1. Introduction

A good understanding of two-phase thermosyphon loops is crucial for further development and optimization of efficient cryogenic cooling loops. Specifically for the development of efficient moderators for cold neutrons it is of paramount importance to understand the thermosyphon loop and its dynamic characteristics.

Although the development of cold neutron sources already started in the 1970's, the current development of stronger neutron sources (for instance at the European Spallation Source [1]) calls for the investigation of the efficiency of the cooling design. Also, as in case of the OYSTER project of the Delft University of Technology [2], if optimization of the performance of both neutron moderation and cooling efficiency is needed, a detailed knowledge of the cooling process involved is required. In case of a two-phase thermosyphon loop, the void fraction inside the moderator cell is a critical factor for efficient moderation of neutrons. For a two-phase flow, the void consists of gaseous moderator (for instance hydrogen or deuterium vapor) which has a much smaller density than the liquid part. However, for optimal moderation, density is

a critical parameter and hence the actual void fraction in the moderator cell determines the performance of the neutron source.

A numerical model is created to study trends in the dynamics of the thermosyphon loop. The model is based on a linear finite element division of the loop where each element has certain characteristics. The model is solved using the principles of conservation of mass, energy and momentum.

Similar models have been constructed in literature by for instance Dobson [3,4], Kaya [5], Bielinski [6] and Zhang [7]. The main difference here is the way that the flow dynamics are incorporated. Basically, it comes down to acknowledging the fact that *temperature changes due to (changing) heat flows are in general much slower than pressure changes due to changing mass flows*. Hence, the acceleration term of the flowing mass is ignored and a steady flow state is assumed at every time step. This is known as the *quasi-static motion approximation*. The mass flow in and out an element is the same. However, if this is strictly followed the mass in the element cannot change. To mitigate this, it is assumed that mass transport from one element to another is adiabatic, where the total entropy of the mass is constant.

2. System description

The moderator cell and its content are cooled by means of a shell and tube heat exchanger. The moderating material itself is

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used to transport the heat load from the moderator cell towards the heat exchanger. The transport is provided by the thermosyphon principle as shown in Fig. 1. The heat load is due to the nuclear gamma and fast neutron radiation accompanying the cold neutron radiation. Also, thermal and cold neutron capture in both moderator and moderator cell wall contribute to the heat load.

The thermosyphon is a loop containing an evaporator (moderator cell), a condenser (heat exchanger) and a buffer volume. The driving force for the mass transport is gravity-based and therefore fail-safe. A buffer volume is connected to the loop for inventory control and storage during the hot or non-operating mode of the loop. The gaseous moderator rising in the riser is condensed in the tubes of the heat exchanger by means of film condensation. The condensation heat is removed by sufficient helium flow. The condensate is not sufficient to block the condensing tubes inner diameter, hence the gas pressure in heat exchanger is almost a static pressure. Further, the diameter of the downcomer should be sufficiently large to let a liquid film drop into the moderator cell. In the downcomer the film is changed into a complete filled tube, from which point the pressures starts to increase due to the weight of the liquid column. Then, there is also some slight sub-cooling of the liquid. In the moderator cell the liquid is evaporated, taking up the heat load. The vapor bubbles accelerate (almost without friction) to the top of the moderator cell where they merge and enter the riser. The vapor is then raised to the top of the heat exchanger, where the loop restarts. The pressure drop during the transport through the riser is compensated by the pressure provided by the weight of the liquid column.

Under static conditions, the complete heat load provided to the moderator cell (and other parts) is transported to the heat exchanger and removed by the helium. Under dynamic conditions the temperature of all parts change in time and the temperature dependent heat capacity of all items must be taken into account.

It is essential to treat the moderator cell differently from the supply and return lines: it is closer to pool boiling than to normal two-phase flow in pipes. This is treated in A. A similar argument holds for the tube side of the heat exchanger. This is much closer to plate condensing than to normal two-phase flow. This is treated in B.

Simulations of thermosyphon loops have been performed by for instance Dobson [3,4], Bielinski [6] and Zhang [7]. However in these cases a limited temperature range has been applied where the loop is either always single-phase or two-phases. Here we need

the behavior between room temperature and cryogenic temperature so that the transition from 1 phase into 2 phases and vice versa should be considered. This is implemented by an appropriate form of the conservation laws.

3. Method

The method is based on the use of a 1D finite element method as used previously by Dobson [4]. All the parts of the thermosyphon loop (see Fig. 1, left side) are coded by means of 1 or more elements that are connected to one, two or three other elements depending on the function of the part. For instance, the riser connecting the moderator cell with the heat exchangers is modeled by 15 elements. The first element of the riser is connected to the moderator element and the last element is connected to the heat exchanger. In this way a loop of elements is constructed from heat exchanger via the downcomer to the moderator cell and via the riser back to the heat exchanger. The mass flow in this loop is everywhere the same. In a similar way another series of elements is constructed between the buffer and the heat exchanger where the mass flow is also constant, although different from the mass flow in the loop (see Fig. 1, right side). The same is done for the parts of the helium loop. The loops are connected at the heat exchanger, where the heat load of the heat exchanger of the thermosyphon loop equals the heat sink of the heat exchanger of the helium loop.

The mass flow through the elements results in a pressure drop because of the friction with the wall. The momentum pressure drop due to evaporation or condensation is neglected (see Appendix F). For constant mass flows, starting from the pressure in the buffer, all pressures in the elements are fixed. The simulation is performed by defining a time step and determining for each element the heat load or sink during that time step. This heat load or sink changes the enthalpy of the contents resulting in a changed pressure and temperature in an element. This change in pressure and temperature give rise to a change in mass in the element that is calculated by means of the concept of adiabatic mass transport resulting in pressure and mass flow changes. After the new masses and pressures have been calculated the next time step is applied.

3.1. Definition of an element

An element is defined as a container interacting with the environment and the material inside the container with 1–3 inputs

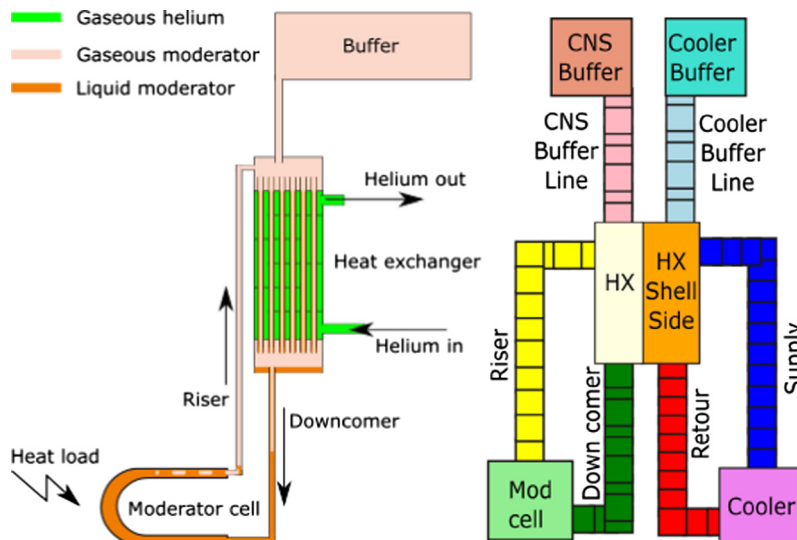


Fig. 1. Thermosyphon loop (left) divided in linear elements (right).

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