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Derivation of integral energy balance for the manotea facility

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HIGHLIGHTS

- An integral energy balance was derived for the MANOTEA facility.
- A second equation was derived which frames transients in terms of inventory alone.
- Both equations were implemented and showed good agreement with experimental data.
- The equations capture the physical mechanisms behind MANOTEA transients.
- Physical understanding is required in order to properly model these transients with TRACE.

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ABSTRACT

Rapid-condensation-induced fluid motion occurs in several nuclear reactor accident sequences, as well as during normal operation. Modeling these events is central to our ability to regulate and ensure safe reactor operations. The UMD-USNA Near One-dimensional Transient Experimental Apparatus (MANOTEA) was constructed in order to create a rapid-condensation dataset for subsequent comparison to TRACE output. This paper outlines a derivation of the energy balance for the facility.

A path integral based on mass and energy, rather than fluid mechanical, considerations is derived in order to characterize the physical mechanisms governing MANOTEA transients. This equation is further simplified to obtain an expression that frames transients in term of liquid inventory alone. Using data obtained from an actual transient, the path integral is implemented using three variables (change in liquid inventory, liquid inventory as a function of time, and change in metal temperature) to predict the outcome of a fourth independently measured variable (condenser pressure as a function of time). The implementation yields a very good approximation of the actual data. The inventory equation is also implemented and shows reasonable agreement. These equations, and the physical intuition that they yield, are key to properly characterizing MANOTEA transients and any subsequent modeling efforts.

1. Introduction

Reactor safety research directed at clarifying Small Break Loss of Coolant Accidents (SB-LOCAs) became a major focus of effort in the aftermath of Three Mile Island. Numerous experiments have been performed to address various aspects of the phenomena occurring during these accidents. Abramson (1985) proposed a classification for the entire range of SB-LOCA events and describes in general terms the various phenomena that occur during a gradual loss of primary inventory. The series of events encountered during a transient is sometimes termed a 'transient sequence'. Duffey and Sursock (1987) analytically described the phenomena in terms of flow characteristics. These studies present the development of a transient in terms of gradual variations in fluid mechanical properties such as pressure, phase separation, or flow rate – essentially describing transients in terms of 'states' (in the thermodynamic sense). Data from Semiscale (Loomis, 1987), Flecht-Seaset (Hochreiter, 1985) and LOFT (Nalezny, 1985) reinforced the usefulness of this approach. However, it should be noted that these facilities were originally designed to analyze large break transients during which fluid inertia effects dominate. MIST (Geissler et al., 1987) and the UMCP Thermal-hydraulic Loop (Hsu et al., 1987) – which were designed to simulate small break transients – found that this approach is not necessarily useful for the characterization of integral systems in which fluid inertia effects are small.

Based on observations made at the UMCP facility, Di Marzo et al. (1988) re-classified the phenomena based on mass and energy transport, rather than fluid mechanical, criteria. Furthermore, they suggested that such analysis might be better suited for predicting transient sequences in general. In a separate work, di Marzo and co-workers showed that a portion of an SB-LOCA is controlled by rapid condensation occurring near saturation conditions (Wang

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Nomenclature

DPHE double-pipe heat exchanger
EZNFXXYYEZNF bete nozzle designator, XX: diameter, YY: spray geometry; IDinner diameter
SB-LOCA small break-loss of coolant accident
MANOTEAUMD-USNA Near One-dimensional Transient Experimental Assembly
NRC Nuclear Regulatory Commission
RELAP Reactor Excursion & Leak Analysis Program
TRAC Transient Reactor Analysis Code

Symbols
Bi Biot number
c specific heat
E energy
L, l length
m mass
P, p pressure, ratio of pressures
q heat transfer per unit mass
R gas constant
r radius
T temperature

Subscripts
L, l liquid
m metal
p pipe
sat saturated
sp spray

Greek
Λ $h_f - h_g$
χ proportionality constant

et al., 1992). These works highlight the integral nature of an SB-LOCA, meaning the current state is the cumulative result of all the previous states encountered in sequence. Furthermore, the transient chronological scale is dictated by how much inventory has left the system.

Rapid condensation induced fluid motion is not limited to SB-LOCAs, but occurs in numerous other accidents sequences and operating situations. Block (1980), Bankoff (1980), and Kirchner and Bankoff (1985) each wrote overview papers summarizing numerous condensation induced fluid motion relevant to reactor operations.

The UMD-USNA Near One-dimensional Transient Experimental Assembly (MANOTEA) is an integral, rapid-condensation facility in which inventory is gradually transferred from a boiler to a condenser during a transient (Pollman, 2011; Pollman and di Marzo, 2012). The facility was designed and built to create a rapid-condensation dataset for subsequent comparison to output from the TRAC (Transient Reactor Analysis Code)/RELAP (Reactor Leak Analysis Program) Advanced Computational Engine (TRACE) plug-in to the Nuclear Regulatory Commission's (NRC's) Symbolic Nuclear Analysis Package (Pollman et al., 2012).

In this paper, we derive a path integral based on the energy partition concept described in our previous work (Pollman and di Marzo, 2012). This derivation highlights the integral nature of the MANOTEA facility and reinforces the validity of framing transient behavior in terms of mass and energy considerations. It also demonstrates the legitimacy of using the energy partition concept to capture and characterize the physical mechanisms behind a MANOTEA transient.

2. Facility description & operation

Fig. 1 is a simplified schematic showing the major components of the MANOTEA facility and the progression of a transient from initial conditions to natural termination. The facility has three major components: a vertical boiler pipe (6.40-m tall, 0.0762-m ID, insulated carbon steel pipe with a 1-kW heater fixed in the base), a vertical double-pipe countercurrent heat exchanger (DPHE) (6.40-m tall, 0.0254-m jacket ID, 0.00635-m copper tube pass-thru ID), and a vertical condenser pipe (6.40-m tall, 0.0762-m ID, insulated steel pipe with a 1-kW heater fixed in the base and a nozzle fixed to the end of the copper tubing which runs from the base of the boiler pipe through the DPHE and terminates in the upper end of the condenser pipe). Each pipe has a volume of about 29.2-L (0.0292-m^3). Detailed balance of plant and instrumentation information is available in Pollman (2011), but beyond the scope of the present discussion.

A typical transient begins with a fixed amount of liquid (29.2-L) in the boiler pipe and enough water to ensure the heating element in the condenser pipe is covered (3.80-L). Both pipes are heated to, and then maintained at, predetermined initial conditions. At this point, heaters are turned off, secondary water is allowed to flow from top to bottom in the double-pipe heat exchanger, and a solenoid valve at the top of the condenser pipe is opened to initiate the transient. Warm, single-phase inventory exits the bottom of the boiler, enters the bottom of the double-pipe counter-current heat exchange and travels upward via the copper tubing. Highly subcooled liquid exits the DPHE and enters the top of the condenser where it is sprayed into the vapor space via nozzles of various size and geometry. The transient is allowed to continue until it self-terminates. Final inventory and transient duration are dictated by nozzle size and geometry. Liquid mass leaving the boiler will always be equal to the liquid mass entering the condenser. Exact initial conditions, final inventory data, and detailed experimental procedures are outlined in Pollman (2011), but these details are not needed for the present discussion.

Regardless of nozzle size or geometry, every transient is controlled by a competition between the energy stored in the metal masses of the condenser wall and the enthalpy of the incoming spray. When a jet nozzle is used, the majority of the incoming (negative) enthalpy is dedicated to collapsing the vapor space. When a fan nozzle is used, a portion of the incoming enthalpy collapses vapor and the balance goes to changing the internal energy of the condenser wall via spray cooling. We call this effect the energy partition.

Inventory flow rate is governed by the pressure difference between the condenser and boiler vapor space. The energy partition dictates condenser pressure, while vaporization rate dictates boiler pressure. During scoping experiments, it was verified that the vaporization rate in the boiler is always sufficient to allow transients to progress unhindered. This observation, and knowing

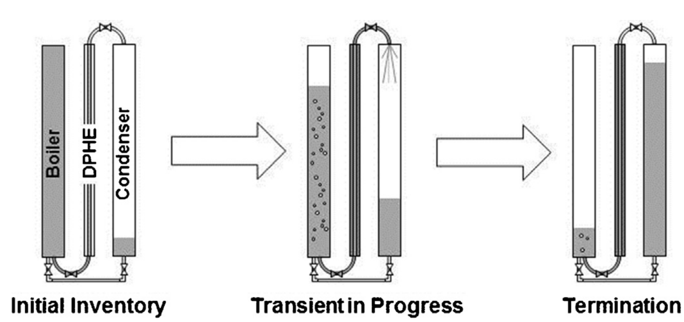

Fig. 1. Schematic drawing showing progression of MANOTEA transient from initial conditions to termination.