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Reduced order model of a two-phase loop thermosyphon by modal identification method

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ABSTRACT

This study focuses on the model reduction of a two-phase loop thermosyphon. The aim is to propose a nonlinear reduced order model able to mimic the thermo-hydraulic behavior of the loop in order to use it for real-time state feedback control, in future applications. First, the one-dimensional two-phase flow model describing the liquid-gas mixture in both mechanical and thermal equilibrium is recalled. The numerical resolution of this detailed model is carried out using a finite volume approach and a Harten-Lax-van Leer Contact Riemann solver. Then, from this detailed model, a new structure of reduced model is determined via the Galerkin projection method. These reduced models, built by the Modal Identification Method, show a very good agreement between the outputs of the detailed model and those computed by the reduced model, during the identification stage. Two test cases, corresponding to different thermal loads at the evaporator, show that the overall levels of density, velocity, mass flow rate, pressure, temperature and internal energy in the loop are satisfactorily reproduced by the reduced model with a global relative error less than 5%. The interest of using such a model lies in the significant gain in CPU time.

1. Introduction

Heat dissipation due to power electronics increases continuously for years, reaching now 300 W·cm^{-2} and beyond, due to electronic components miniaturization. Highly efficient cooling systems are then required. As the classical cooling systems are not powerful enough, an interesting solution consists in using two-phase heat transfer devices, since the cooling capabilities are much larger with latent heat than with sensible heat. Among them, a two-phase loop thermosyphon (2PLT), for which the fluid circulation is generated by buoyancy forces, is a passive cooling system without pump. The working fluid boils at the evaporator due to heat input. The vapor then moves to the condenser where heat is extracted from the system and the vapor changes to liquid. These two-phase closed thermosyphons have been studied in many applications such as, solar water heaters [1–4], telecommunication equipments [5], avionics systems [6], nuclear power plants [7–9], electronics industry [10].

Many studies have been carried out on the modeling of such a system in steady and transient states. For instance, Vincent and Kok use 1D control volume approach for the transient behavior of a two-phase co-current thermosyphon [11]. Different models are used for evaporator, condenser, liquid line and vapor line. This means that for computation, each part of loop has its own model. They are based either on hydraulic flow model or compressible flow model. More recently, Bieliński and Mikielewicz present a generalized 1D two-phase separate flow model of the thermosyphon loop [12]. They use incompressible flow model with Boussinesq approximation and empirical correlation in different parts of the loop. This model considers thermal equilibrium at any point of loop. Qu uses two different models for evaporator and condenser [13]. An integral balance of bubble flow model is used at the evaporator and the liquid film condensation of vapor-liquid concurrent flow model at condenser.

In this paper, a 1D model (Euler equations) is used to describe the transient operation of a simplified loop thermosyphon (constant cross-section, adiabatic liquid and vapor lines, single evaporator) [14]. In each part of the loop, the same model is used in the computation. In other words, the model describes thermodynamic equilibrium (saturation or mixture), but also thermodynamic non-equilibrium (pure liquid or pure vapor) phase and so can compute phase transitions (liquid-mixture-vapor). This simplified model retains the main features of a real 2PLT: gravity-driven two-phase compressible flow, unsteady behavior, thermodynamic equilibrium and non equilibrium. Despite its simplifying

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Nomenclature

a	state vector function
A	duct cross-section, m^2
B	coefficient involved in closure laws, Pa
C_p	specific heat, J·kg^{-1}·K^{-1}
d	internal diameter, m
e	specific internal energy, J·kg^{-1}
g	acceleration of gravity, m.s^{-2}
h	specific enthalpy, J·kg^{-1}
h_{cond}	condenser heat exchange coefficient, W·m^{-2}·K^{-1}
H	output matrix
$\mathcal{J}_{id}^{(m)}$	quadratic functional to be minimized for order m model identification
L	length of the loop, m
m	ROM order i.e. size of vector a
$\dot{m}$	evaporation/condensation rate per volume unit, kg·m^{-3}·s^{-1}
N_x	number of cells for space discretization
N_t	number of time steps
p	pressure, Pa
P	heat power density source term, W·m^{-3}
q	specific reference energy, J·kg^{-1}
$\dot{Q}_{evap}$	thermal load at evaporator, W
S_{ext}	exchange surface at condenser, m^2
t	time, s
T	temperature, K
T_{cold}	cold external temperature at condenser, K
u	velocity, m·s^{-1}
υ	specific volume, m^3·kg^{-1}
v	generic notation for variables
x	position along the loop, m
y	vapor mass fraction

Greek symbols

γ	specific heat capacity ratio
δv	deviation of variable v with respect to initial steady state
δt	time step, s
ε_{glob}	global relative quadratic error between DM and ROM
ε_v	relative quadratic error between DM and ROM for variable v
$\phi_k^{(v)}$	kth space function associated with variable v
μ	dynamic viscosity, kg·m^{-1}·s^{-1}
ρ	density, kg·m^{-3}
Ω	volume, m^3

Subscripts

0	initial steady state
eq	thermodynamic equilibrium
g	gas
id	identification
l	liquid
neq	not in thermodynamic equilibrium

Superscripts

T	transposition sign
(v)	related to variable v

Abbreviations

2PLT	two-phase loop thermosyphon
DM	Detailed Model
MIM	Modal Identification Method
ROM	Reduced Order Model
SG	Stiffened Gas

assumptions, this model requires large CPU time consumption, even in 1D, especially because of the Courant-Friedrichs-Lewy (CFL) condition. It is hence not usable for real-time applications. In the present paper, this model is used as starting point to build a Reduced Order Model (ROM) of this 2PLT. A ROM is a model involving a small number of degrees of freedom, which reproduces the behavior of an actual system or a reference Detailed Model (DM) with a large number of degrees of freedom, whatever the time-varying boundary conditions and/or source terms.

The goal of this work is to develop a nonlinear ROM able to mimic the thermo-hydraulic behavior of the loop in order to use it for real-time state feedback control, in future applications. To the author's knowledge, this work constitutes the first attempt to develop a ROM of a 2PLT.

Among model reduction methods for nonlinear problems, let us first cite the Proper Orthogonal Decomposition (POD), also known as Karhunen–Loève decomposition, coupled to a Galerkin projection. As a result of performing POD on discrete space-time data, a set of space functions and time-varying coefficients are obtained, that allow compact approximation of original data. After truncation or selection of modes, a reduced set of space functions is retained for a Galerkin projection of Partial Differential Equations (PDE) onto these space functions, which yields a so-called POD-Galerkin ROM. Although this approach has been widely used in the last decades, especially in fluid mechanics, either for buoyancy-driven flows [15,16], two-phase flows [17] and compressible flows [18], it is known to often lead to unstable ROMs, even in the case of linear PDE, thus requiring a posteriori stabilization [19].

Another approach is the Reduced Basis (RB) method [20] which aims at building ROMs able to compute solutions of parametrized PDE for given value(s) of parameter(s). It is a two-step approach. In the offline step a reduced basis is built, formed by solutions of a reference Finite Element model at optimally selected points in the parameter space via a Greedy algorithm. The online step consists in solving the ROM which is obtained by a Galerkin projection of PDE onto the reduced basis. Although the RB method can be applied to transient flow problems, directly or by coupling it to POD as done for instance in [21] for natural convection in cavity, it appears to be adapted to the construction of parametric ROMs for parameters which are not time-dependent rather than for time-varying external or internal loads. It should be mentioned that the RB method provides errors bounds but in return requires a reference Finite Element model on which it relies [20].

The goal oriented model-constrained approach developed by Bui-Thanh et al. addresses some POD-related issues by computing the basis of space functions via an optimization problem: minimizing the output error between reference model and ROM solutions, subject to satisfying the ROM equations. It is assumed that each basis vector can be represented as a linear combination of snapshots. The approach has been applied in [22] to a compressible flow around a rotor blade, showing that for a small number of approximation functions ($\leq$10), stable ROMs have been obtained whereas POD-Galerkin ROMs were unstable.

The Proper Generalized Decomposition (PGD) does not rely on a reference model and does not make use of simulated or measured data. PGD uses approximations for the variables under separate form, which are sums of products of functions of space coordinates,