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Multi-Mode Physical Modelling of a Drum Boiler

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Abstract

Multi-mode modelling and simulation is the ability to switch between states that describe different operating conditions, for instance: turning subsystems on or off, phase appearance or disappearance (e.g. vapor within liquid), switching to a dysfunctional mode (e.g. pump cavitation or breakage), switching controllers, etc. Cyber-physical systems exhibit frequent mode switching. Models with multiple modes may exhibit varying structure since modes may have different levels of detail, hence different numbers of degrees of freedom or state variables. When switching modes, state variables may appear or disappear dynamically. The simulation of such systems is a fundamental difficulty that has been successfully addressed recently within the European MODRIO project by designing and implementing a new Modelica hybrid-state machine in the modelling and simulation tool Dymola. This new hybrid-state machine has been used to model phase appearance and disappearance in thermal-hydraulic volumes. The fundamental physical equations for the one-phase and two-phase modes and the conditions for transition between modes are presented and simulation results are given for the industrial test-case of a drum boiler. Thermal-hydraulic volumes are fundamental components in the staggered grid scheme used to model thermal-hydraulic systems, so the result solves the general problem of phase appearance and disappearance in thermal-hydraulic systems.

Keywords: multi-mode behavioural modelling; thermal-hydraulics; hybrid-state machine; Modelica;

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1. Introduction

Power plants are cyber-physical systems (CPS) that exhibit a large number of operating modes of all kinds: normal modes such as startup, shutdown or nominal operation, and dysfunctional modes such as component failures, leaks, spurious phase appearance or disappearance… Large conventional power plants such as nuclear power plants are most of the time operated under steady state conditions. However when the system is operated away from its nominal condition, modes switching occur, following planned or spurious events. The growing share of renewables on the power grid means that large conventional power plants will be more often operated away from their nominal operating point, leading to less revenue for the operator and increased wear for the plant. It also means that more spurious events may occur, originating e.g. from the power grid, leading to system faults or failures. To minimize these drawbacks, it is necessary to optimize large plant transients such as startup, shutdown, load following or islanding with respect to costs while complying with operational constraints. It is also necessary to analyze the behavior of the system in the presence of more diverse origins of faults or failures. This requires the ability to model and simulate mode switching.

Multi-mode modelling and simulation (M&S) is the ability to switch between states that describe different operating conditions. Some examples are: turning subsystems on or off, appearance or disappearance of a phase (e.g. vapor) within another phase (e.g. liquid), switching to a dysfunctional mode (e.g. pump cavitation, pump breakage, valve leakage), switching controllers, etc. CPS exhibit frequent mode switching. Transitions between modes may be deterministic (e.g. turning a subsystem on or off as required by an operating procedure), or probabilistic (e.g. breakage of a pump due to excess wear). Multi-mode M&S is necessary to be able to explore the consequences of an initiating event on the system that may lead to mode switching. It is thus necessary for designing and verifying fault-resilient systems against requirements.

Models with multiple modes may exhibit time-varying structure since modes may have different levels of description detail, hence different numbers of degrees of freedom or state variables. When switching modes, state variables may appear or disappear dynamically. Also, the physical behavior of CPS modes are best described by differential-algebraic equations (DAEs).

There is a well-known approach in automata theory called hybrid automata that is able to handle multi-mode systems if the modes are described by ordinary differential equations (ODEs). However, for CPS this approach is not feasible because the physical equations in the form of implicit DAEs must be converted into explicit ODE form, and the number of needed states to do so can grow very rapidly.

Therefore the simulation of mode switching in CPS is a fundamental difficulty that has been recently successfully addressed within the MODRIO project by designing and implementing the prototype of a new Modelica hybrid-state machine in Dymola[1]. The new hybrid state machine generalizes the concept of hybrid automata to systems described by DAEs, with deterministic or stochastic transitions guarded by events (transitions may be instantaneous or delayed, depending on the current state). It also introduces a new dimension in modelling modularity: the ability to add new modes to a model component without modifying existing ones. It is therefore now possible to adapt progressively existing models to simulate dysfunctional situations.

The objective of this paper is to show how the generic problem of phase appearance or disappearance in a thermal-hydraulic volume may be solved using this new prototype.

Nomenclature

ρ	fluid density (kg/m^3)
V	fluid volume (m^3)
$\dot{m}$	fluid mass flow rate (kg/s)
h	fluid specific enthalpy (J/kg)
u	fluid internal energy (J/kg)
x	mass fraction of vapor within the two-phase mixture (-)

Subscripts l refer to the liquid phase. Subscripts v refer to the vapor phase.