CATHARE2 V1.4 CAPABILITY TO SIMULATE THE PERFORMANCE OF ISOLATION CONDENSER SYSTEMS WITH THERMAL VALVE

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ABSTRACT

ENEA (Italy) in co-operation with CEA (France) has carried out an R&D activity aimed at increasing the reliability of Decay Heat Removal (DHR) passive systems that implement in-pool heat exchangers. The main outcome reached was the definition of a device, called Thermal Valve (TV), able to avoid the installation of mechanical valve on the primary circuit, thus reducing thermalmechanical constrains and thermal-hydraulic instabilities.

This paper presents a preliminary assessment performed with CATHARE of this innovative device. In the first part the code capability to simulate in-pool heat exchangers is verified against experimental data of the PANDA facility, that are available within the frame of the ISP 42. In the second part a CATHARE calculation showing the performances of the PANDA passive condenser with TV (start-up and shutdown) is described.

1 INTRODUCTION

The definition of new strategic safety goals for the future reactors has brought over the last years a safety improvement and a substantial simplification in its implementation. This result has been obtained in particular thank to the development of innovative passive safety systems. These innovative passive systems cover the main safety functions: reactivity control, Decay Heat Removal (DHR), Fission Products containment.

The reliability and efficiency assessment of such innovative safety systems requires numerical analyses able to provide a realistic prediction of all the physical phenomena concerned. Thermal-hydraulic system codes, like RELAP, CATHARE and TRAC, which could be used to this purpose, are not validated in the peculiar scenarios (low pressure, condensation in presence of noncondensable gases, e.g.) characterizing most of the systems. For this reason the uncertainty on analytical results is still very high. ENEA (Italy) and CEA (France) within the frame of an EU FISA Project [1] have studied an innovative device, called Thermal Valve (TV), able to increase the reliability of DHR system implementing in-pool heat exchangers in natural circulation, like for example the Isolation Condenser (IC) of the SBWR. This device, enables the control of the removed power by modifying the thermal exchange conditions in the pool, thus avoiding the installation of mechanical valves on the primary circuit and reducing thermalmechanical constrains and thermal-hydraulic instabilities.
Some preliminary studies showed that the representation of the pool at atmospheric pressure and the prediction of the condensation within the Heat Exchanger (HX) tubes were the most critical issues for the CATHARE simulation of IC systems [2] [3]. The CSNI International Standard Problem (ISP) 42, based on PANDA facility, has allowed testing a CATHARE model for in-pool heat exchangers against experimental data. This comparison has highlighted how the new set of constitutive relationships (Revision 6) implemented in the latest version of CATHARE (v1.5) strongly improves the simulation of in-pool heat exchangers in natural circulation. These results have allowed the analytical assessment of the TV concept in the PANDA IC configuration with a sufficient level of confidence.

2 THERMAL VALVE

2.1 Isolation Condenser System

Although the Thermal Valve is a device applicable to all DHR systems implementing in-pool heat exchangers in natural circulation, the present work refers to an Isolation Condenser System. The general validity of the preliminary assessment of the device is not affected by the peculiar system considered.

The Isolation Condenser system is designed to remove excess sensible and core decay heat from the BWR reactor by natural circulation, when the normal heat removal system is unavailable. Its main purpose is to limit the overpressure in the reactor system at a value below the set-point of the Safety Relief Valves (SRV), preventing unnecessary reactor depressurization. The system (fig.1a) basically consists of a number of totally independent loops, taking into consideration a redundancy degree, each loop contains a heat exchanger that condenses steam on the inner tube side and transfers heat to the water in a large pool. The primary side of the condenser, connected to the reactor pressure vessel by piping, is located in the reactor building, above the source of the steam (vessel). Closed valves in each line prevent condensation during normal power operation of the plant. The condenser tubes and the drain piping are filled with condensate which is maintained at subcooled temperature by the pool water. When operation of the IC system is required, the valves are opened, the condensate drains into the reactor vessel by gravity and the steam flows directly from the reactor into the condenser. The flowrate is determined by natural circulation.

![Fig. 1: Isolation Condenser: Standard Configuration and Configuration with TV](image-url)
2.2 New Configuration with Thermal Valve

The Thermal Valve device, based on a concept developed by CEA within the frame of studies for innovative systems for future reactors [4], allows to increase the reliability of IC systems by avoiding the implementation of mechanical valves on the primary circuit. The control of the thermal exchange is achieved by modifying the thermal exchange conditions in the pool (Fig 1b). Moreover this configuration is applicable to all the systems provided with in-pool heat exchangers operated by mechanical valves.

The Thermal Valve is made up of a diving bell submerged in the pool surrounding the in-pool heat exchanger, provided with a valve (pilot valve) on the upper part of the bell and open in the lower part (Fig 2).

The thermal exchange control in the new configuration is transferred to the TV pilot valve. At IC standby condition the pilot valve is closed (2a), the steam produced is confined under the bell and the natural circulation is drastically reduced as well as the power exchanged. Following sudden reactor isolation the valve is opened (2b), then the steam is released and condensed in the pool, while the cold water flows from the opening in the lower part of the bell. When effective natural circulation is established (2c) both in the primary loop and in the pool, the heat exchanged through natural circulation has to limit the reactor pressure below SRVs set point for a long duration. The pilot valve closing (2d) provokes the confinement of the steam produced under the bell until the heat exchanger isolation and the natural circulation stop.

![Thermal Valve Functioning](image)

**Fig 2:** Thermal Valve Functioning
3 ANALYTICAL MODEL

3.1 CATHARE Nodalization

The theoretical assessment on the IC system with TV has been planned in order to verify that such new control, proposed instead of mechanical valves, allows to fulfill the functional specifications and the performance requirements of the system itself. The latest version V1.5a of the system code CATHARE [5] has been selected to this purpose, since a comprehensive analytical model of the plant permits to calculate the system performance and the plant response in a wide spectrum of operation and accident conditions. CATHARE and the system codes in general are not completely qualified for the peculiar scenario characterizing the system (low pressure, condensation inside the tubes), so a validation of the model against experimental data is essential to reach a appropriate level of confidence on the analytical results.

Figure 3 shows a sketch of the CATHARE nodalization developed to study Isolation Condenser Systems implementing the Thermal Valve device. As regards the calculation of IC performance during steady state conditions, the complete simulation of the primary loop is not necessary (Fig. 3a). The primary circuit is limited to the condenser while the steam source (vessel) has been simulated by means of two boundary conditions imposing steam pressure, enthalpy and flowrate. The pool is simulated as two volumes representing the upper and the lower plenum and two axial elements standing for the water surrounding the heat exchanger and the pool recirculation. The axial element surrounding the heat exchanger has the shape and the volume of the TV bell, besides the pilot valve is simulated with a valve element. The atmospheric pressure on pool surface and the make-up to restore the boiling level are imposed by means of two boundary conditions. The thermal coupling between the condenser and the pool is simulated by a wall structure representing the condenser tubes thickness.

Transient calculations require a more detailed model of the primary loop (Fig. 3b), to demonstrate the capacity to start and stop the natural circulation both in primary and in secondary side by acting the pilot valve. Vessel, steam line and drain line are added to the previous nodalization. The core decay heat is simulated by means of heating walls in the vessel.

![Fig. 3 : CATHARE Nodalization of IC with TV](image)
3.2 Analytical Model Assessment

A number of CATHARE applications [2] [3] [6], performed during the last few years for studying Isolation Condenser Systems, showed some code inadequacies in simulating in-pool steam condensers in natural circulation. In particular, the heat transfer for condensation within tubes resulted quite underestimated in all applications. The reason for this was recognized in the inadequacy of the Shah correlation used to calculate heat flux density in film condensation regime.

The standard version v15a contains a new set of constitutive relationships (Revision 6) including an improved condensation model based on Chen correlation [7]. The CSNI International Standard Problem (ISP) 42 [8], based on PANDA facility, has allowed testing this new correlation as well as the CATHARE model developed for in-pool heat exchangers. In fact, as already said, the representation of the pool at atmospheric pressure is an additional point that requires special attention.

3.2.1 ISP42 Description

PANDA [8] is a large-scale facility which has a modular structure of cylindrical vessels interconnected by piping. The facility, designed so as to reproduce the thermalhydraulic behavior of the SBWR under the conditions of a LOCA occurring 1 hour after scram, was configured in the ISP42 to simulate the containment of a passive BWR. Six pressure vessels represent the Reactor Pressure Vessel (RPV), equipped with electric heaters simulating the core decay heat generation, Drywell (DW) and Wetwell (WW) (two vessels each) and the Gravity Driven Cooling System pool. Four rectangular pools, placed in the upper part of the facility, can be equipped with immersed heat exchangers that for advanced BWR represent the condensers of the PCC (Passive Containment Cooler) and IC systems.

The test for ISP42 was subdivided in six sequential phases with initial and boundary conditions defined separately in order to focus such phase on a restricted number of phenomena. ENEA and CEA participate in the ISP, within the frame of a co-operation on the assessment of CATHARE mainly concerning the simulation of passive systems for advanced reactor. Phases A, C and D of the ISP, which cover all the functioning states of the PCCS (start-up, long term operation and pure steam conditions) resulted the most interesting to be calculated since they cover all the functioning states of the PCCS (start-up, long term operation and pure steam conditions) for the study of Passive Heat Removal Systems implementing pool immersed heat exchangers. Phase D, in particular, concerning the investigation of the system behaviour in case of PCCS overload at pure steam conditions, is representative for typical functioning of IC system.

3.2.2 Assessment Results

Post-test analysis of the three phases calculated [9] has confirmed the capability of CATHARE to simulate the overall response of the facility under different conditions and to reproduce some phenomena of special interest for the study of passive safety systems of evolutionary LWRs. Concerning the heat removal by condensation in PCCs, the large instrumentation of the component and the different functioning conditions covered by the three phases analysed allow a comprehensive verification of the models involved. The comparison between calculation results and experimental data shows that the new correlation of Chen for condensation within tubes slightly underestimates the thermal exchange at high concentrations of non-condensable gas and slightly overestimates it at low concentrations.

In case of pure steam conditions (phase D) the results are reported in the following. The test was conducted with two PCCs connected to DW in operation starting from a constant
RPV power of about 800 kW equivalent to their heat removal capacity. In figure 4 are reported the starting power predicted in three calculations distinguished by different correlations for the thermal exchange. It is evident the improvement obtained by using the Chen correlation in the Revision 6. Besides, a further slight improvement issues from a new correlation proposed for pool boiling on the basis of an experimental campaign conducted by CEA in EPICE facility.

The increase of power up to 1400 kW at the beginning of the transient led to system pressurisation because the PCCs was already working at full capacity. When the overpressure exceeded the hydrostatic head due to the main vent lines submersion, the steam was vented into the wetwell pool where it was condensed, thus slowing down the system pressurization. The pressure evolution is consequently determined by two mechanisms that counter the system pressurization. The calculation reproduces very well this evolution (Fig. 5), even if a slight compensation between the two mechanisms is supposed to be present. The slight overprediction of the PCCs pool levels (Fig. 6) and of the temperature drops within PCCs
tubes (Fig. 7) confirm that CATHARE is able to properly simulate the performance of in-pool heat exchangers in natural circulation.

4 TV APPLICATION TO PANDA IC

In order to assess the TV concept in analytical way, a CATHARE simulation of the start-up and shut-down of the PANDA IC with TV has been carried out. This calculation represents only a preliminary exercise, in fact, a comprehensive assessment would require several calculations on an industrial size, aimed at evaluating the heat removal capacity and at confirming the stability of the natural circulation in all normal and out-of-normal scenarios foreseen.

The accidental transient selected concerns the IC start-up and shut-down in a situation of sudden reactor isolation and TV pilot valve trip. The IC is initially at standby conditions with the pilot valve closed and negligible exchanged power. Initial conditions for primary system are typical of the SBWR plant (298 °C and 84 bar), while the pool is conservatively at saturation conditions. Following sudden reactor isolation, the primary power simulating the core decay heat (1 Mw) causes pressure increase up to the pilot valve set point (92 bar), the valve is opened and the heat exchanged through natural circulation has to be enough to keep the reactor pressure lower than the SRVs set point. Stable and effective natural circulation has to guarantee safe shutdown conditions for a long duration. When pilot valve is closed again the steam produced under the bell isolates the heat exchanger stopping the natural circulation.

Most relevant results of the calculation are reported in figures 8 and 9. Exchanged power and primary pressure (Fig. 8) seem to confirm the validity of the TV concept:

- start of the natural circulation both in the pool and in the loop at the pilot valve opening on imposed set point,
- natural circulation effectiveness to limit the reactor pressure,
- stop of the natural circulation and heat exchanger isolation (negligible exchanged power) at the pilot valve closing.

Strong oscillations in pool mass flowrate (Fig. 9) indicate the unstable behaviour of the convective flow in the pool. The reason for this seems to be the presence of a relevant pressure drop due to the pilot valve in the boiling length of the natural circulation loop. An improvement in the design, like a larger valve flow area or a different configuration that locates the valve at the lower opening of the bell, could overcome the problem.

![Fig. 8 : Reactor Pressure and Exchanged Power](image1)

![Fig. 9 : Pool and HX Tubes Mass Flowrate](image2)
5 CONCLUSIONS

A CATHARE model of the Isolation Condenser System has been developed to study an innovative device, Thermal Valve, proposed to increase the reliability of this system. Experimental data, available within the frame of an international exercise (ISP-42), have allowed verifying the model in order to get a sufficient level of confidence in the analytical assessment of an IC system provided with TV.

A preliminary application on a scaled IC System (PANDA) has confirmed the effectiveness of the TV in operating such kind of systems, even though the final design requires further feasibility studies.

REFERENCES


