A THERMO-HYDRAULIC TOOL FOR AUTOMATIC VIRTUAL HAZOP EVALUATION

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Abstract

Development of complex lubrication systems in the Oil&Gas industry has reached high levels of competitiveness in terms of requested performances and reliability. In particular, the use of HazOp (acronym of Hazard and Operability) analysis represents a decisive factor to evaluate safety and reliability of plants. The HazOp analysis is a structured and systematic examination of a planned or existing operation in order to identify and evaluate problems that may represent risks to personnel or equipment. In particular, P&ID schemes (acronym of Piping and Instrument Diagram according to regulation in force ISO 14617) are used to evaluate the design of the plant in order to increase its safety and reliability in different operating conditions. The use of a simulation tool can drastically increase speed, efficiency and reliability of the design process. In this work, a tool, called TTH lib (acronym of Transient Thermal Hydraulic Library) for the 1-D simulation of thermal hydraulic plants is presented. The proposed tool is applied to the analysis of safety relevant components of compressor and pumping units, such as lubrication circuits. Opposed to the known commercial products, TTH lib has been customized in order to ease simulation of complex interactions with digital logic components and plant controllers including their sensors and measurement systems. In particular, the proposed tool is optimized for fixed step execution and fast prototyping of Real Time code both for testing and production purposes. TTH lib can be used as a standard SimScape-Simulink library of components optimized and specifically designed in accordance with the P&ID definitions. Finally, an automatic code generation procedure has been developed, so TTH simulation models can be directly assembled from the P&ID schemes and technical documentation including detailed informations of sensor and measurement system.

Keywords: RT code prototyping, lube oil console, Rotating machine HazOp analysis, transient behaviour analysis, Plant-Control System interaction.

1. Introduction

The object of this work is developing a tool, called TTH lib (acronym of Transient Thermal Hydraulic library), for the mono-dimensional analysis and simulation of thermo-hydraulic systems and in particular of auxiliary and lubrication plants of turbo machines. TTH lib has been customized for the simulation of oil lube plants, with a particular attention to the application to virtual HazOp analysis (acronym of Hazard and Operability). For this purpose, the response of the simulated plant is heavily influenced by delays, reduced bandwidth and nonlinear behaviour of the installed measurement and actuation systems. Consequently, attention is also focused on modelling of these components. This work is a product of cooperation between the University of Florence (in particular the Mechatronics and Dynamic Modelling Lab) and the industrial partner GE NP (acronym of General Electric Oil & Gas Nuovo Pignone sited in Florence, Italy).

At the end of the work, TTH lib is planned to be only a part of a more complete simulation environment called Virtual HazOp Toolbox. In this research paper, the two terms will be interchangeably used without considering the difference between the single module (TTH lib) and the complete simulation environment. In particular, one of the most important innovation of the proposed tool is introducing the HazOp philosophy in a simulation toolbox, providing HazOp team with an important tool for evaluating control systems and process systems itself. The work tackles an important combination between process safety and simulation of process responses, thus leading to better design of process measurements and the assurance of technical safety. Currently Thermal hydraulic simulations are performed using several well recognized commercial software tools, such as Mentor Graphics Flowmaster™, LMS Amesim™ or Aspen Hysys™. All these tools have been validated by a wide population of users both in the academic and industrial fields, such as in the examples [1, 3]. This paper represents a feasibility study for introducing the concept of Prognostics and Health Management into the GE Nuovo Pignone failure analysis. Moreover, the proposed tool can be seen as a tradeoff among different features proposed by renown commercial software and the internal specifications of GE NP procedures. In particular, as an initial step different failures have been analysed and compared with numerical and experimental data, in order to validate the proposed simulation tool. For the development of TTH lib the following specifications have been considered:

- Automatic model generation: a simulation model is automatically generated assembling a pre-defined population of sub-models directly from the GE technical database and documentations available in PidXP™; PidXP™ is the P&ID (piping and instrument diagram) drafting tool used by GE NP . Automatic Model Generation from plant sketches is used to reduce errors introduced by data transcriptions and operator misbehaviour. In order to ease the automatic creation of the model, consistency of exchanged data has to be automatically confirmed and verified.

- Co-Simulation of GE NP controllers: GE NP uses the HIL-SIL (acronyms of Hardware In the Loop and Software In the Loop) approaches for the development and verification of controllers. At present, these activities are performed using Matworks™ Matlab Simulink tools. Consequently, it is very important to maintain compatibility with Matworks™.

Considering the above mentioned specifications two main requisites of the tool have to be assured:

- Optimization for Fixed Step solvers and Real Time implementation: considering the previously described application for HIL and SIL testing, the tool has to be used for fast prototyping of the Real Time code. These applications involve using fixed step solvers to obtain a deterministic task time with pre-defined computational resources. Also Automatic generation of C-code for a real time target has to be supported;

- Robustness: the tool has to be used for simulating virtual Haz-Op (component failures or off-design conditions) during the design process. Simulation of failures often correspond to ill conditioned models, that should be difficult to be treated from a numerical point of view. Consequently, robustness and stability of the simulation code is a mandatory specification.

2. Description of equations

2.1 Fluid Properties: Approximated Polynomial Formulation

One of the aims of the proposed tool is to simulate the thermal hydraulic transient of a plant, considering off-design conditions. These conditions are often associated to pressure-temperature working ranges where the fundamental properties of the fluids such as viscosity and density change in an appreciable way.

In the proposed tool the real behaviour of the fluid is modelled, considering the variability of physical properties as polynomial functions of fluid pressure (p) and temperature (T). In particular, fluid properties are extrapolated with respect to the reference pressure (p_{ref}) and temperature (T_{ref}) conditions. Specific volume v_s is extrapolated with the 2nd order polynomial law (1) respect to a reference value, v_{so} :

$$v_s = v_{so}\left[1+a_{p1}\left(p-p_{ref}\right)+a_{p2}\left(p-p_{ref}\right)^2+a_{t1}\left(T-T_{ref}\right)+a_{t2}\left(T-T_{ref}\right)^2+a_{pt}\left(p-p_{ref}\right)\left(T-T_{ref}\right)\right].$$ (1)

The absolute viscosity μ is approximated by an exponential law (2) whose exponent ψ is interpolated with the 2nd order polynomial law; μ_o represents the viscosity value calculated with respect to the reference pressure and temperature conditions:

$$\mu = \mu_0 10^{\psi}; \quad \psi = b_{p1}\left(p-p_{ref}\right)+b_{t1}\left(T-T_{ref}\right)+b_{t2}\left(T-T_{ref}\right)^2.$$ (2)

The specific heat coefficient c_p is interpolated in the same way as adopted for v_s (3). In this case calculation is also performed with respect to the reference value of c_p called c_{po}.

$$c_p = c_{p0}\left[1+c_{t1}\left(T-T_{ref}\right)+c_{t2}\left(T-T_{ref}\right)^2+c_{p1}\left(p-p_{ref}\right)+c_{pt}\left(p-p_{ref}\right)\left(T-T_{ref}\right)\right].$$ (3)

For the thermal conductivity λ sensitivity against pressure is neglected, so interpolation (4) is performed considering the reference value λ_o and the corresponding dependence on temperature.

$$\lambda = \lambda_o\left[1 + d_{t1}\left(T - T_{ref}\right) + d_{t2}\left(T - T_{ref}\right)^2\right].$$ (4)

The proposed approach implies a simple expression of fluid properties, obtained using Taylor series in the linearization process. Also partial derivatives of v_s, μ, c_p and λ with respect to p and T can be easily calculated since derivatives of polynomial functions are known and can be explicitly written in a closed form. As an example, the partial derivative of λ is simply described by the following equation obtained by deriving (5):

$$\left(\frac{\partial \lambda}{\partial T}\right)_p = \lambda_o d_{t1} + 2d_{t2}\left(T - T_{ref}\right).$$ (5)

2.2 Discretization of the system

The general approach followed in literature [4–7], for a mono-dimensional flow, is described in terms of mass conservation, momentum and enthalpy balances based on the following equations (6),(7),(8).

$$\frac{d\rho}{dt} = \frac{\frac{dm}{dt} - \rho\frac{dV}{dt}}{V(t)},$$ (6)

$$\rho\left(\frac{\partial v_x}{\partial t} + v_x\frac{\partial v_x}{\partial x}\right) = -\frac{\partial p}{\partial x} - f_x,$$ (7)

$$dq_T + \frac{dp}{\rho} = dh,$$ (8)

where the following symbols are adopted:

ρ, V fluid density and volume;

h, q_T enthalpy and exchanged heat flux;

x, v_x are the length, position and speed of the fluid;

t time;

In order to reproduce the dynamical behaviour of thermal hydraulic systems, PDEs (Partial Differential Equations) (6), (7) and (8) have to be solved. According to the examples in literature [6]–[8] and commercial software [9], the simulated plant is discretized in lumped elements where equations (6),(7),(8) are re-written in terms of discrete mass, momentum or energy balances. In this way, the system can be modelled as an ODE (Ordinary Differential Equation) system which can be solved using Matlab-Simulink™. In particular the plant is discretized using the following lumped elements:

- *RI* (Resistive and Inertial) elements: in this element only the momentum balance is implemented. Inlet and outlet conditions in terms of pressure *p*, temperature *T* are imposed by an external source or calculated by an adjacent capacitive element. In this way it's possible to calculate mass and enthalpy flows passing through the modelled component. If the momentum balance (7) is implemented considering only the steady state response (time derivatives are neglected) the corresponding equations are simplified. In this case the corresponding element is called *R* or pure resistive element, as shown in Figure 1. Typical components modelled as resistive components are valves, orifices and more generally components associated to relevant pressure losses.

- *C* (Capacitive) element: the component is modelled as a lumped volume (or capacity) where energy and mass balances are performed to calculate local values of *T* and *p*. Inlet and outlet mass Q_m, and enthalpy Q_h flows are assumed to be imposed or calculated by adjacent resistive components. Since energy and mass balances are implemented also heat and mechanical power exchanges can be modelled with this element as shown in the scheme in Figure 1. Typical components that can be modelled as capacitive elements are tanks, heat exchanger, actuators, etc.

- T and special Junction blocks: since complex hydraulic circuits are composed by networks with several loops, hybrid elements (composed of Resistive and Capacitive elements) are used to connect multiple loops.

- Imposed Source Block: to impose boundary conditions, as for example an assigned pressure-temperature source or an assigned flow, simple terminator blocks should be added to the simulation scheme.
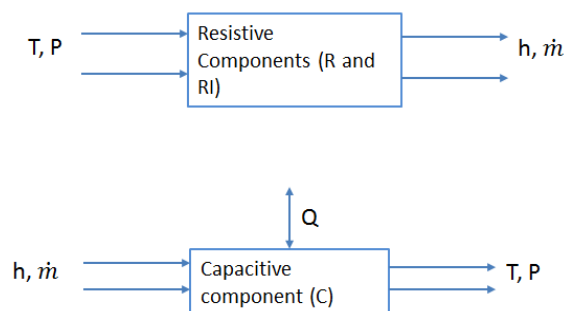

Fig. 1. Description of the resistive and capacitive elements.

2.3 Resistive Elements: implemented equations

In the scheme presented in Figure 2, it is considered a uniform flow in a pipe with a constant section *A*, length *l* and angle α, relative to the ground. In this case, the momentum balance (7)

should be re-written as (9), where Q_v is the volumetric flow [m³/s] assumed to be homogenous along the pipe:

$$\rho l \frac{dQ_v}{dt} = \left(p_1 - p_2\right) A - \xi(Re) \frac{\rho \left|Q_v\right| Q_v}{2A} - \rho g \sin\left(\alpha\right) Al. \tag{9}$$

The term ξ represents the viscous friction factor which is calculated as a function of Reynolds Number and the different loss factor. In the form described by (9), the model is able to calculate Q_v as the output from known boundary pressure and temperature conditions which are the inputs of the model, as shown in the scheme in Figure 2.
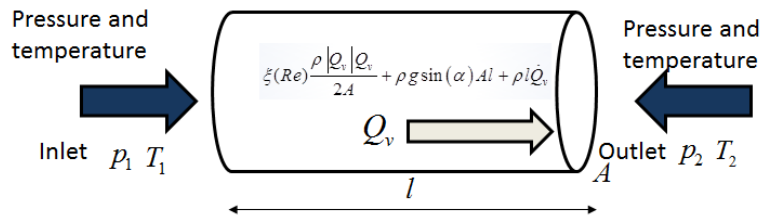
Fig. 2. A sketch of a general RI element: inlet and outlet pressure and temperature values are assumed as the input, calculated flow is the output of the *R* element.

In many applications contribution of the time derivative terms is negligible; as a result the equation (9) can be re-written in a simpler form (10).

$$\left(p_1 - p_2\right) A - \xi(Re) \frac{\rho \left|Q_v\right| Q_v}{2A} - \rho g \sin\left(\alpha\right) Al = 0 \tag{10}$$
$$\Downarrow$$
$$Q_v = f\left(p_1, p_2\right).$$

The equation (10) is a pure algebraic relation that can be solved without any additional integrator block; in this case the element is simply called R (or 'pure resistive'). The mass flow Q_m is directly calculated from the volumetric flow rate Q_v and the density value of the inlet section according to (11). The enthalpy flow is computed according to (12) which is valid assuming conservation of enthalpy in the flow passing through the component.

$$Q_m = \rho Q_v, \tag{11}$$
$$Q_h = h Q_m. \tag{12}$$

Using the R and RI components allows simulation of different components such as distributed or lumped pipe losses, orifices and valves. In particular, valves are modelled as orifices with variable area and flow coefficients. For valves the response of the component is implemented using standard Matlab-Simulink™ blocks. It is worth to note the possibility to model hydraulic actuators (such as pumps and motors) using a customized version of (10). In this case Q_v is calculated to model actuator behaviour as a function of an external input such as pump imposed rotational speed. As an example a centrifugal pump is described in terms of load ϕ and ψ flow coefficients. Consequently, the relation (13) should be adopted to describe the behaviour of this kind of component:

$$Q_v = f\left(p_1, p_2, n\right) = f\left(\phi, \psi, n\right), \tag{13}$$

$$\phi(\psi) = \frac{Q_v}{nc_\phi}; \quad \psi = \frac{p_1 - p_2}{n^2 c_\psi}; n = \text{rotation speed};$$

$$c_\phi, c_\varphi, \text{ characteristic coefficients.}$$

Enthalpy exchanges introduced by hydraulic actuators have to be evaluated for the calculation of the proper enthalpy flow. In particular, the specific enthalpy h delivered in the outlet section has to be coherently recomputed taking into account the exchanged mechanical work calculated in (8). Considering the delivered hydraulic power W_h and the efficiency of the pump $\eta(\phi, \psi)$, it is possible to compute the mechanical power W_m and the required torque T_m. As consequence, also a pump or an actuator/motor should be modelled as a customized Resistive block.

2.4 Capacitive Elements: implemented equations

Mass balance (6) can be applied to the control volume presented in Figure 3 to determine the density ρ. Consequently, knowing the properties of the modelled fluid it is possible to calculate the corresponding pressure derivative according to (14):

$$\frac{dp}{dt} = \beta \left[\frac{1}{\rho} \frac{d\rho}{dt} + \alpha \frac{dT}{dt} \right] = \beta \left[-\frac{1}{v_s} \frac{dv_s}{dt} + \alpha \frac{dT}{dt} \right], \tag{14}$$

$$with: \begin{cases} \alpha = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P = \frac{1}{v_s}\left(\frac{\partial v_s}{\partial T}\right)_P \\ \beta = \frac{\rho}{\left(\frac{\partial \rho}{\partial p}\right)_T} = \frac{1}{v_s\left(\frac{\partial \rho}{\partial p}\right)_T} = \frac{-v_s}{\left(\frac{\partial v_s}{\partial p}\right)_T} \end{cases}.$$

From the energy/enthalpy balance (8) re-written in a simplified form (15) it is possible to calculate the temperature derivative in the control volume:

$$\frac{dT}{dt} = \frac{Q_{h1} - Q_{h2} - \rho(dV/dt)h + Q_T}{Vc_p} v_s + \frac{1}{c_p} T\left(\frac{\partial v_s}{\partial T}\right)_P \frac{dp}{dt}. \tag{15}$$

As a result of integrating equations (14) and (15), the temperature and pressure profiles of the control volume are evaluated. The corresponding scheme of the capacitive block is presented in Figure 3.
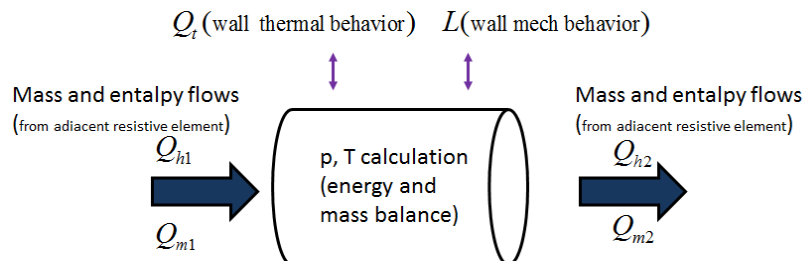

Fig. 3. The control volume considered for mass and enthalpy balance.

It is also possible to model a change of the volume capacity, due to the wall flexibility. For this purpose a wall function $V(p)$ is introduced in order to calculate the internal volume as a function of the fluid pressure. With this method it is possible to model the effect of a generic real pipe wall with an elastic behaviour. By customizing $V(p)$ function, it is also possible to

model the variable volume chamber of a simple effect actuator coupled with a mechanical impedance. Finally, the variable volume of pressurized tanks should be modelled as a particular case of capacitive elements by properly modelling the wall function. Energy balance (15) takes also into account the exchanged heat flow Q_t. Consequently, as it was previously said, also heat exchangers can be modelled as capacitive elements.

3. Thermal-Hydraulic tool implementation

3.1 Simulink-Simscape Implementation

As it was discussed before, a high compatibility and interoperability with internal GE models and engineering tools were a part of the product specifications. The proposed tool is developed as a standard Matlab-Simulink-Simscape™ library where both lumped capacitive and resistive components are modelled as customized blocks. Also, more complex components and subsystems can be modelled as arrays of capacitive and resistive elements. In this case blocks are masked and their internal structure is transparent for the final user. The code is optimized for RT execution, considering fixed step computation and compatibility with almost all the supported target compilers. The typical appearance of blocks inside the Virtual HazOp toolbox is masked as a standard Simulink component, to guarantee manageability of the parameter customization without need of having additional know-how by the user. As shown in the scheme in Figure 4, implementation of a plant using Resistive and Capacitive elements involves a bi-directional data exchange between lumped components of the simulated network. Mathworks™ has developed its own tool for the simulation of multi-physic networks (commercially known Simscape™) and the bi-directional data exchange between blocks is performed using customized Simscape™ signals and blocks. In this way a complete compatibility between the Virtual HazOp toolbox and the corresponding Multi-physics tools of Mathworks™ (also including solvers optimized for the simulation of physical networks) is assured. The command signals or the access to internal states of the component are implemented as a standard Simulink Input-Output port. The graphical aspect of each component is decided by graphical commands that can be changed according to the desired standard used for plant designing such as ANSI Y32.10 (commonly used for fluid power applications) or P&ID, mostly derived from ISA standard S5.1 Instrumentation Symbol Specifications. In particular, relevant data concerning sensors of the plant, such as expected bandwidth or non-linear phenomena (dead zones, hysteresis, etc.), should be automatically configured in the model exploiting information available in a dedicated database linked to P&ID schemes.

3.2 Lumped Pipe Models

Also pipes are modelled using lumped **RI**, **R** and **C** components. Different kind of pipe models should be used according to the level of required accuracy and simulated scenario. In particular, pipe submodels should differ depending on the number or the kind of discrete lumped elements used. As default, pipe connections are generated using the simpler pipe model compatible with the adjacent connected elements.

3.3 Automatic Model Generation

In order to reduce errors and delays due to model transcription and data transcription from technical documentation, the Simulink model is automatically generated from P&ID schemes taken from GE PidXP™ configuration tool (an engineering tool/database for the definition and sketch of hydraulic systems). Using a tool internally developed by GE, the user is able to automatically extract a network topology from a P&ID scheme of the hydraulic system: each component is associated with the corresponding database of properties and technical

information. In this way it is possible to automatically generate a plant model using remote construction instructions. The topology of the generated model is almost equal to the corresponding P&ID scheme since there is a univocal correspondence between P&ID symbols and corresponding Simulink models. Even relative positions of components are reproduced to define an intuitive approach. It is important to notice that since the model is created in Matlab-Simulink™, further customization and modifications are still possible. Also, most of the parameters are masked and the blocks are accessible as a standard masked subsystem. The workflow corresponding to Automatic Model Generation from GENP PidXP™ is schematized in Fig. 4.
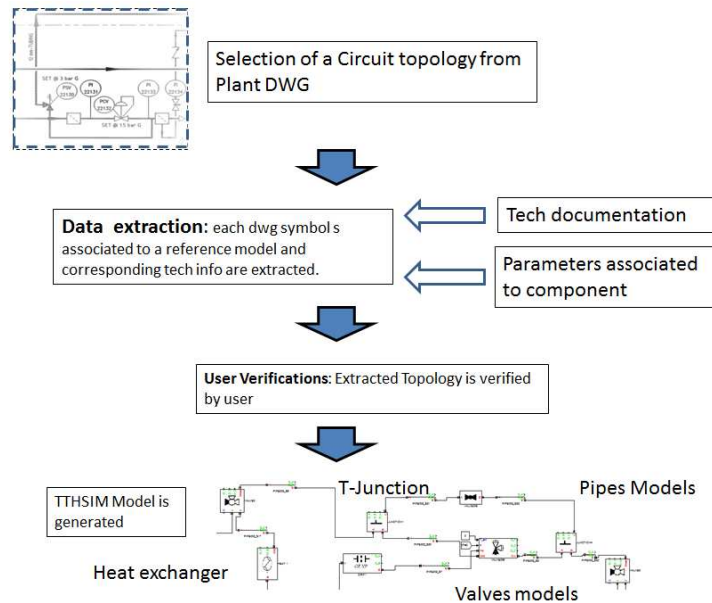
Fig. 4. Typical workflow from GE P&Id scheme to the corresponding Virtual HazOp toolbox.

It is interesting to notice that the software is designed with a modular approach so an expert user may directly drop blocks to produce his own heavily customized code for simulation. On the other hand, standard analysis can be also performed by intermediate and entry level users following an automated-guided process, which drastically reduce the risk of human errors and assure a safe and repeatable way of working.

3.4 Optimizing integration and solving methods

The proposed tool is implemented in Matlab-Simulink™ and all the supported solvers can be used; however, considering GE specifications, code optimization and benchmark tests executed by authors, some considerations should be done. Simulations of thermo-hydraulic systems (and more generally of multi-physics systems) involve numerical troubles:

- Numerical stiffness: associated, for example, with the rigid behaviour of the fluid (which is near to uncompressible).
- Non-linear behaviour: a hydraulic plant is composed of elements with highly non-linear behaviour which often produces strong discontinuities in the shape of the calculated solutions.
- Mixed DAE (Differential Algebraic Equations) and ODE (Ordinary Differential Equations) systems: Combinations of both DAE and ODE equations involve the use of a very robust solver.

Since the feasibility of RT simulation plays an important role in the tool specifications, the authors have optimized the code in order to privilege robustness when used with fixed step solvers. In this way, implementation of plant models requires limited computational

resources allowing the use of both low integration frequencies and low order solvers. For this kind of applications, implicit solvers proved to be more stable in comparison with explicit ones. In particular, the '*ode14x*'[10], which is an extrapolation solver based on the linearly implicit Euler method [11–12], has been preferred because it represents the best compromise in terms of stability and numerical efficiency. A stabilizing pre-run is also typically performed, in order to increase the consistency of the imposed initial conditions and consequently to avoid potential numerical troubles in the model initialization phase. Efficiency and stability troubles also arise in virtual HazOp analysis where it is required to perform long or multiple simulation patterns in which different or worst case scenarios have to be analysed. Consequently, stability represents a hard issue since simulation of 'stressed' plants often involves implementation of bad conditioned physical systems operating in a situation which is quite far from the nominal one. Also, in this case implicit solvers have proved to be a better compromise between performance and stability. However, the user has the possibility to associate the application of a failure scenario with changing integrator parameters, splitting an analysis in a sequence of coherent simulations with different solving tolerances: more relaxed for time-consuming situations, more demanding for bad conditioned ones. In this way, since the user knows the sequence of simulated events in the plant, he should plan a forced change of solver parameters associated to a known event which has proven to be hard to be simulated.

4. Preliminary validation

Debugging and validation are quite onerous tasks. This activity has been preliminary performed by means of several benchmark cases analysed with the GE supervisors obtaining a direct feedback in terms of knowledge, practice and experimental data from the existing plants. The validation activities are still going on, but preliminary results are encouraging.

A preliminary debug of the code is performed comparing results obtained with the proposed tool and a commercial code. The comparison is made on a simplified benchmark model (starting from elementary components to simplified scenarios which are considered meaningful with respect to the final use). Preliminary cross-verification with a commercial code is considered mandatory in order to verify numerical performances and the correctness of the implementation on known-assigned models. Among the various tests performed, in this work the authors focus their interest on the plant described in Fig. **5**. The benchmark plant is referred to a mineral lube oil console used to guarantee the proper pressure and mass flow to the auxiliary systems of a compressor (in this case, the hydrodynamic journal bearings). In the proposed work, the authors according with GE NP plant designers simulate the bearings as an equivalent orifice described by means of a GE NP formula. According with the GE NP requirements, in the Virtual HazOp procedure the main physical variables evaluated from the user are the following ones:

- *Load pressure*: the load pressure is measured at the output of the lube oil console;

- *Collector pressure*: the pressure is measured at the intersection between the two pumps;

- *Main pump pressure*: the pressure is measured at the outlet of the pump;

- *Auxiliary pump pressure*: the pressure is measured at the outlet of the pump.

- *TCV temperature*: the temperature after the TCV (acronym of Temperature Control Valve). This is the valve used to control the temperature of the lubricant by mixing refrigerated and hot oil.

The hydraulic load, i.e. the bearings of a turbo-machine, is modelled as an equivalent orifice (Load in Fig. **5**55), and has to be fed with an assigned inlet pressure. The inlet pressure is self-

regulated by a PCV (acronym of Pressure Control Valve). The inlet flow to the PCV is assured by a centrifugal pump moved by an asynchronous motor; in case of failure, to increase the system reliability, a parallel backup pump is activated. An asynchronous motor is modelled considering a known-tabulated speed-torque response *Te(n)* provided by GE NP. A filtering transfer function is introduced to model inertial and viscous friction mechanical loads (16).

$$T_e(n) - T_m = J_m \frac{dn}{dt} + fn \Rightarrow n = \frac{T_e(n) - T_m}{J_m s + f},$$

$$J_m = \text{mech. inertia}; \ f = \text{friction factor.}$$

(16)

During the failure of the pump, the pressure of the PCV is stabilized by a pressurized tank, called PT in the scheme presented in Figure 5. A 3-way valve (TCV) is used to stabilize oil temperature at the pre-defined value of 50°C by regulating the volumetric flow passing through a cooler (modelled as a composite *R-C-R* resistive, capacitive component). The cooler is simulated assuming a constant heat exchange coefficient. The inputs of the lube oil console are the command signals of TCV, the main pump and the backup pump. The outputs are temperature and pressure sensor measurements which are distinguished in Figure 5 with red dots. These signals are passed to the model of GE NP controller .The controller regulates PCV, TCV and pumps in order to control pressure and temperature of the load represented by an equivalent orifice. Additional orifices, check valves and by-pass valves are added to the plant. Pipes are modelled as *R-C-R* elements (two resistive and capacitive elements) neglecting the contribution of inertial forces in equations. In Table I, the component parameters of the whole lube oil console are described (according to the GE NP technical documents).
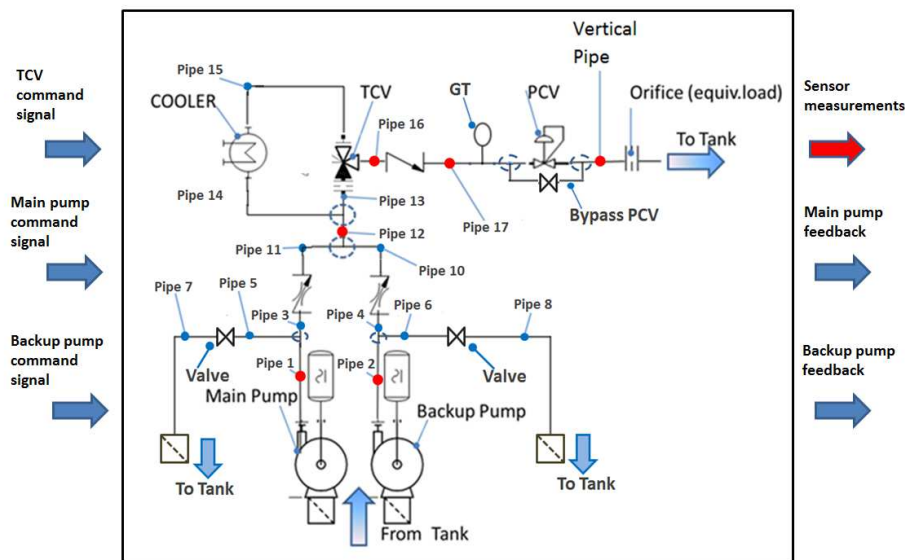

Fig. 5. Lube oil console scheme.

Using the simplified model described above, different failure or operating conditions can be simulated. Failures of the components are defined according with GE NP experiences and each component simulates its failure behaviour. As example, different TCV failures can be simulated:

- The TCV is blocked in a position in which only the cold inlet port is open and the load is fed only with the refrigerated lubricant,

- Failed valve fed the load only with unrefrigerated lubricant.

 Other examples should be related to different failure modes of motors, pumps, etc. Each component of the library is created according with a predefined list of implemented failure modes. Consequently, when the model is assembled from plant schemes, a failure list is automatically created. Each element of the failure list is automatically linked to the corresponding component of the plant model. In this preliminary validation, the lube oil console is modelled both into the virtual HazOp toolbox and in the commercial code, by defining the maximum case of the possible failures; the possible scenarios are increased since its model is also used to verify consequences of the removal of the pressurized tank. In Table II, the list of simulated failure modes is described.

Table 1. Component parameters.

Component	Parameters	Init. Conditions $Q_v(0)$[m³/s],$T(0)$[C°]
Check Valve	0.011m³/s (ΔP=1Bar)	0,43
Check Valve with orifice	0.011m³/s (ΔP=1Bar) Orifice (φ =3mm.)	0,43
PCV	φ=55mm (Full Open) pressure setpoint =2.5bar	0,43
Pressurized Tank	0.6m³ (volume) 2.72 bar (pre-charge)	0,43
TCV	φ=35mm (Full Open) temperature set-point=58C°	0,43
Cooler	φ=35mm, 7850 WK^{-1}	0,43
Pipe elements	length=3, φ=150mm	0,43
Vertical element	length=7, φ=150mm	0,43
Centrifugal pump	Flow-Pressure curve, Flow-power curve	0,43

Table 2. List of failures.

Failure	Description
Pump switch without pressurized tank	The main pump is manually switched off to analyse the response of the controller. The controller has to activate the backup pump.
Pump switch with pressurized tank	The main pump is manually switched off to analyse the response of the controller. The controller has to activate the backup pump.
Opening pump bypass valve without pressurized tank	The pump bypass valve is manually open to analyse the response of the controller. The controller has to activate the backup pump.
Opening pump bypass valve with pressurized tank	The pump bypass valve is manually open to analyse the response of the controller. The controller has to activate the backup pump.
Opening pump bypass valve without pressurized tank with both pumps activated	The pump bypass valve is manually open to analyse the response of the controller.
Opening PCV bypass valve without pressurized tank	The PCV bypass valve is manually open to analyse the response of the controller. The PCV has to become fully open to try to regulate the pressure.
Opening PCV bypass valve with pressurized tank	The PCV bypass valve is manually open to analyse the response of the controller. The PCV has to become fully open to try to regulate the pressure.
Failure cold of the TCV without pressurized tank	The TCV is manually forced to open the cold inlet only. The tank is not present
Failure cold of the TCV with pressurized tank	The TCV is manually forced to open the cold inlet only.

 Results of simulated failures are evaluated considering the measurements described above. Among the various failure list, in this work the authors have focused their attention on the "*Pump switch without pressurized tank"* failure. In this way, it is possible to analyse both the controller behaviour and the thermal-hydraulic stability. In addition, the measured experimental data on a real plant have been provided by GE NP for this failure mode.
The validation phase is divided into two tasks:

- Cross-Validation with a Commercial Code: results of the proposed simulation model are compared with the ones obtained with another commercial software; the aim of

this procedure is to verify coherence of the implementation performed by the authors with the current state of the art.

- Validation with Experimental data: results of the proposed model are compared with experimental data recorded on a real plant.

4.1 Cross-Validation with a Commercial Code

In Fig. **6** some compared results are shown: the simulated collector pressure results obtained with TTH lib and LMS Amesim™ for the plan described in Figure 5 are compared. The following scenario is simulated: the pump switch is enabled at 15 s and the controller starts the backup pump when the pressure is below 7 BarG. As it is clearly seen the results of both simulation software tools are almost the same. In Fig. **7**, for the same simulation scenario, the load pressure is analysed. In this case differences between the two software tools are also quite small. The behaviour of the thermal-hydraulic plant during this failure is coherent with the GE NP experience, because the pressure reaches a minimum value of about 1 BarG showing a response that is coherent with typical design criteria.
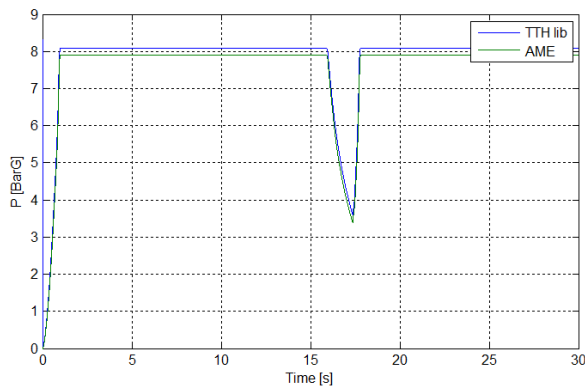

Fig. 6. Comparison of the collector pressure between the Virtual HazOp toolbox and the Amesim model.
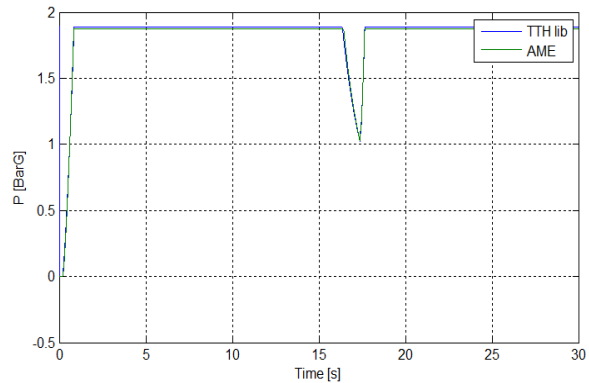
Fig. 7. Comparison of the load pressure between the Virtual HazOp toolbox and the LMS Amesim™ model.

Finally, in Figure 8, the same comparison is performed for the simulated temperature of the lubricant in the outlet section of the TCV. In this case, there are some little differences between the simulated temperature profiles. However, this error should be justified with slightly different control and implementation strategies in the two models.

In order to quantify the relative agreement between the two models in a more rigorous mode, the following error indexes are introduced:

- *Load pressure error*: the maximum relative difference between the load pressures (E_{LP}) calculated by the two simulation software tools;
- *Collector pressure error*: the maximum relative error between the collector pressures (E_{CP}) ;
- *TCV temperature error*: the maximum relative error between the two simulated temperatures at the TCV outlet (E_{TCVT}).

These indexes can be used to describe coherence among the different tests in a synthetic manner. In Table III, the E_{LP}, E_{CP} and E_{TCVT} values calculated for different failure conditions show a good agreement between the two simulation software tools, corresponding to maximum errors of about 2-3%.
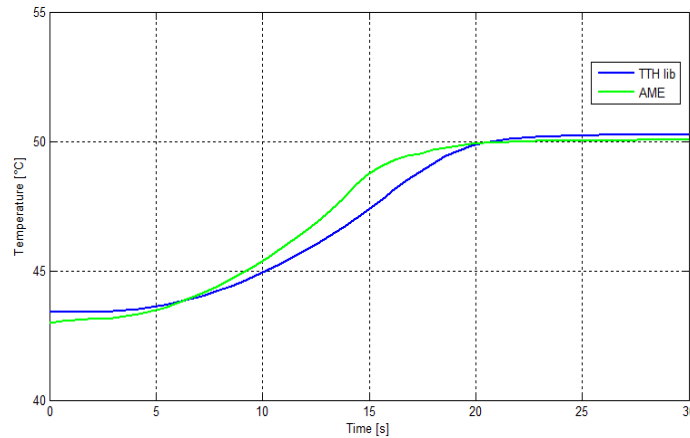
Fig. 8. The temperature in the outlet section of the TCV (comparison between the proposed tool and a corresponding plant model implemented in LMS AMESIM model™).

Table 3. Error evaluations.

Failure	E_{LP}	E_{CP}	E_{TCVT}
Pump switch without pressurized tank	1.2%	2.6%	1.8%
Pump switch with pressurized tank	1.1%	1.3%	2.2%
Opening pump bypass valve without pressurized tank	0.6%	0.7%	1.9%
Opening pump bypass valve with pressurized tank	0.6%	0.9%	1.9%
Opening pump bypass valve without pressurized tank with both pumps activated	0.6%	0.8%	1.9%
Opening PCV bypass valve without pressurized tank	0.9%	1.1%	1.8%
Opening PCV bypass valve with pressurized tank	0.8%	1.0%	1.9%
Failure cold of the TCV without pressurized tank	0.6%	0.9%	1.0%
Failure cold of the TCV with pressurized tank	0.6%	0.9%	0.9%

The failures in Table III are proposed by the GE NP partner and represent the main critical situations in which the lube oil console has to be examined; this study represents a test-case and can be seen as a feasibility study to understand and to approach the Prognostics and Health management techniques. Moreover, to establish the preliminary estimation of efficiency of the implemented code, running times of both codes are compared considering fixed and variable step implementation as shown in Table IV. Calculation of computational times is performed using a standard notebook with Intel™ i7core processor and 8Gb of Ram with a Microsoft Windows 7 operating system. For the Matlab-Simulink™ implementation an *rsim target* (a generic non real time target which is used to produce a standalone executable of the code) is used. Considering variable step implementation, various Matlab-Simulink™ "stiff-robust" solvers have been tested, in particular the 'ode23-tb'[10]. In this case, the solver adopted by the commercial software is two or three times faster than the Virtual HazOp toolbox since the simulation performances are heavily affected by the simulated scenario. Considering fixed step implementation (which may be mandatory for RT or HIL applications), the proposed tool exhibits a high stability compared to the chosen integration step which is about 10^{-4} s and can be reduced to 10^{-3}s or less (in many simulation scenarios 10^{-2} s fixed integration step is tolerated). The same plant, when it is executed using the fixed step solvers of the commercial code, involves the use of a fixed integration step which is typically more than ten times smaller. The corresponding difference in terms of global duration of the simulation is much lower (about 40%); this result is only partially

justified by a different kind of solver adopted. Further efforts have to be undertaken to increase the efficiency of the code and to perform smarter implementation because proposed code is still much slower in terms of the turn-around time, i.e. the time required to solve a single integration step.

Table 4. Comparison of simulation performances considering fixed step implementation.

Software	Solver (order)	Solver step [s]	Execution Time[s]
Virtual HazOp toolbox/TTH lib	'ode14x'	10^{-4}	174
Commercial	Euler	10^{-5}-10^{-6}*	290 (min
Commercial	Adams-Bashforth (2)	$2*10^{-5}$-10^{-6}*	285(min)
Commercial	Runge-Kutta (2)	$2*10^{-5}$-10^{-6}*	275(min)

*Stability troubles, by lowering component dynamics the same simulations should be repeated dividing integration step of one tenth; however, the performance ratio doesn't change

5. Validation with Experimental data

The corresponding plant scheme for model validation with the experimental data is shown in Fig. **5**. The objective of this benchmark case is to evaluate both the dynamical behaviour of the thermal-hydraulic system and the GE MKVI controller performance during the pump switch without the pressurized tank. Interaction between the simulated plant model and the GE Regulator is shown in Figure 9. The Software In the Loop analysis is performed, since the regulator model is the same that is used by GE: all the alarm logics and the controller actions are implemented. The experimental tests analysed in this paragraph are referred to String Test performed by GE Nuovo Pignone in the Massa site (Italy). The main parameters to analyse are the load pressure, the collector pressure, the main pump pressure and the backup pump pressure (pressure transient analysis). Moreover, since the simulation model carries out a thermal-hydraulic analysis, a comparison between the temperatures measured after the TCV is made (temperature transient analysis).

Every simulated signal is filtered by a first order low pass filter (17) which reproduces the dynamic behaviour of the pressure-temperature transmitters that the experimental data are referred to.

$$y(s) = \frac{1}{1 + \tau s} \quad where \quad \tau \approx 0.4s \, (diff \,.signals). \tag{17}$$

Simulated failure modes are introduced in the model as programmable input sequences which can be directly controlled by the user or automatically generated by a failure sequence builder. This part of the code is also implemented in Matlab™ in order to automate the process.

The validation is carried out by comparing measured pressure profiles with the corresponding ones calculated using the Virtual HazOp toolbox.

In particular, the following sequence of events is simulated in this work:

• the main pump of the plant without Gas Tank is switched out.

• GE MKVI controller detects the failure and consequently activates a backup auxiliary pump.

• The backup pump is used to restore the normal operating condition of the plant.

Some simulation results referred to the proposed failure sequence are shown in Figures 10−11.

Figure 10 shows the results corresponding to the model in which the response of sensors according to (17) is modelled. Figure 11 shows repetition of the same simulation neglecting the response of the measurement system (perfect measurements with no lag are assumed).

From the comparison between Figures 10 and 11, the decisive contribution of the

measurement and control system is quite evident. The aim of the simulation is to evaluate the capability of the system to restore the proper operating conditions without compromising plant safety.
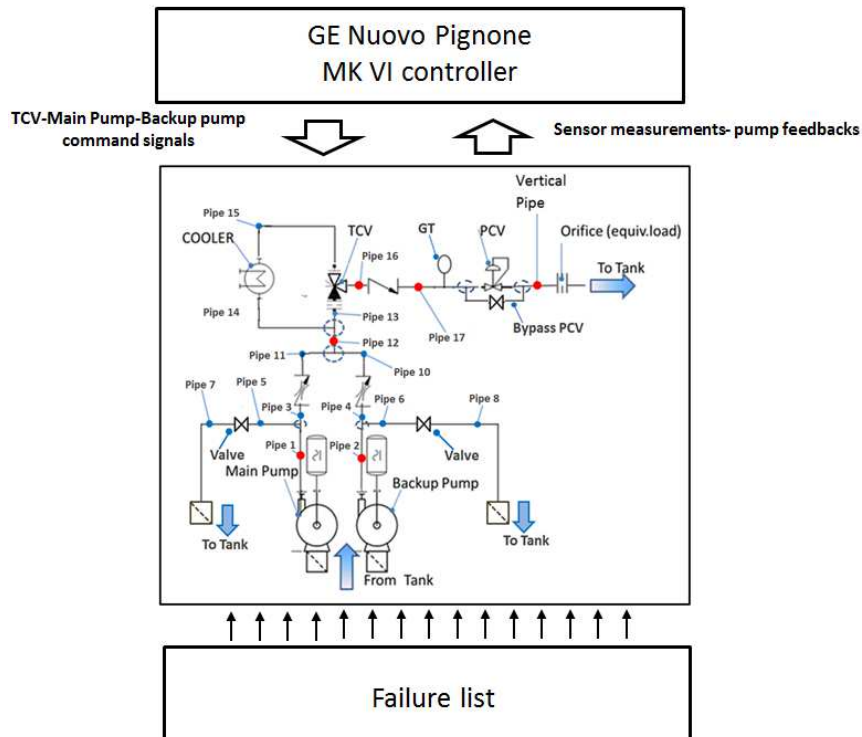

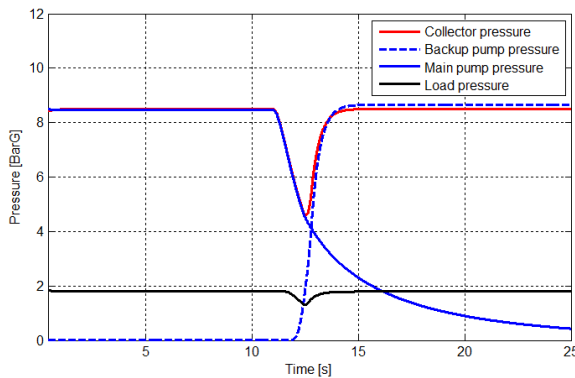Fig. 9. Interactions between the lube oil console, the model of MKVI controller and the failure blocks.

Fig. 10. Dynamical behaviour of the main four pressures (considering the dynamical behaviour of pressure transducers).
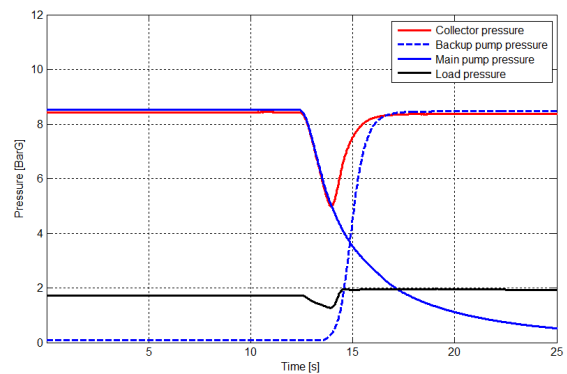
Fig. 11. Dynamical behaviour of the main four pressures (filtering of sensors is not introduced).

Referring to the scheme of lube oil console presented in Figures 5 and 9, the comparison between the Virtual HazOp toolbox and the experimental data of the collector pressure is shown in Figure 12. The behaviour of the measured and the calculated pressure is quite similar, even when considering the uncertainties of component parameters. Fig. **13**13 presents the dynamical behaviour of the main pump after the failure: the pressures decrease along the same curve, which implies that the resistance of the plant is nearly the same. Contribution of the measurement system is also well modelled since the simulated sequence of events is defined as a function of the measured pressure level of the plant.
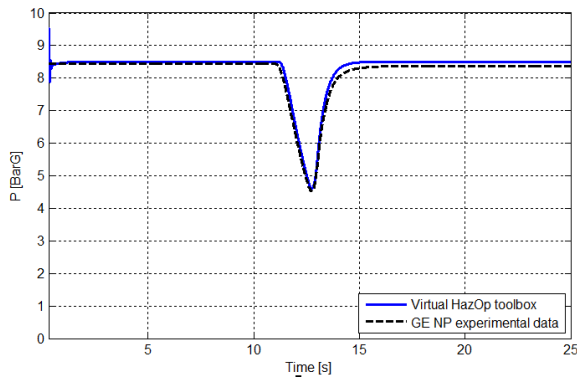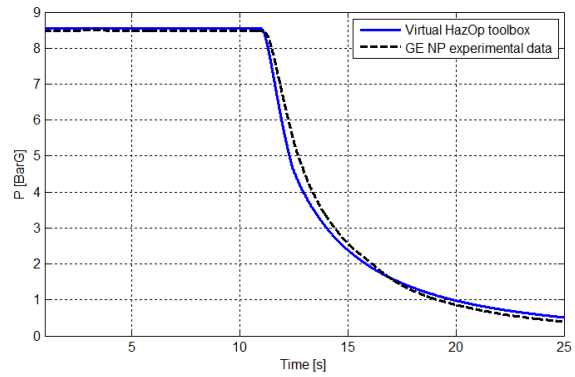
Fig. 12. Collector pressure.

Fig. 13. Main pump pressure.

The validation process analyses also the temperature transient measured by the temperature sensor after the TCV. For this simulation a different scenario is considered: the plant starts from a "cold" condition, during normal working conditions the lubricant is gradually heated until it reaches a stable temperature regulated by TCV valve. The simulation results and experimental data are compared in Figure 14: The temperature transient is longer than the pressure transient due to the thermal inertia of the oil. The TCV is modelled with the datasheet parameters. The data are related to the previous String Test and provide two different starting situations: the initial temperature is about 25°C while the assumed stable temperature is 55°C. Looking at the results shown in Figure 14 small differences in the stabilized temperature between the simulated results and experimental data can be noticed. This differences probably arise from the way the hysteretic behaviour of the TCV is implemented.

The same simulation is repeated assuming a hot starting condition of the plant, corresponding to an initial temperature of the oil of about 49 C°. As shown in Figure 15, there is a good agreement between the simulation results and experimental data obtained by GE NP on the string plant in Massa (Italy). Finally, in order to have a synthetic comprehension of the performance of the model some further results are summarized in Table V: the maximum relative error between the simulation results and experimental data. The comparison contained in Table V has been obtained by processing all the results corresponding to the operating scenarios described in Figures 10 and 12−15.
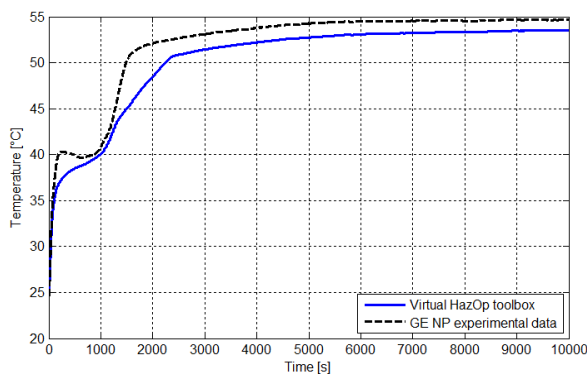

Fig. 14. Comparison between the experimental and simulated data starting from 25°C.
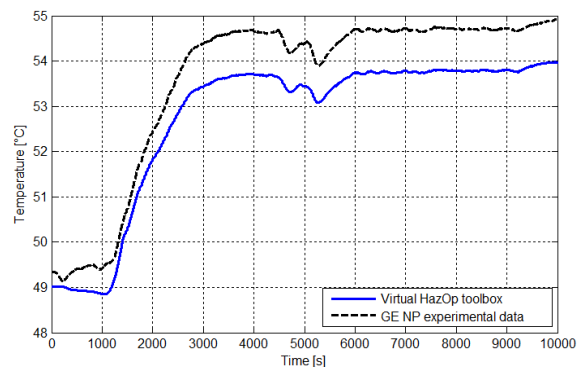

Fig. 15. Comparison between the experimental and simulated data starting from 49°C.

Table 5. Maximum errors.

Transmitter	Maximum errors
Collector Pressure	*<5%*
Auxiliary pump pressure	*<4%*
Main pump pressure	*<5%*
Load pressure	*<4%*

As shown in Figures 10−15 and in Table V, the dynamical behaviour of the lube oil console model and the lube oil console experimental data are quite similar. Differences between the simulation results and experimental data are compatible with errors, tolerances and approximation introduced in modelling of sensor transfer functions, input parameters and - more generally - the complexity of the system. Regarding the temperature transient, the main differences are probably caused by uncertainties in the cooler parameters. Also, major uncertainties - especially in off-design conditions - are introduced by the oil consumptions of bearings which will be further investigated in an experimental campaign which is planned in the next year.

6. Conclusions and further developments

In this work an integrated tool able to simulate Thermal Hydraulic Plants and their interaction with installed measurement and control systems is proposed. The code is validated with the experimental results provided by GE NP. The benchmark test case clearly shows that in order to obtain good simulation results a good modelling of the measurement system is unavoidable. This work can be seen as a feasibility study aiming to introduce, in the future release of the software, the Prognostics and Health management techniques into the GE NP internal procedures. The PHM techniques allow the study of the failure mechanisms related to system lifecycle management. Moreover, inside the Virtual HazOp toolbox a procedure to automatically convert the P&ID scheme of GE Nuovo Pignone into the proper dynamical model is implemented. The main features of this toolbox are its high versatility of Fixed Step solvers for the R-T implementation and compatibility with the GE Nuovo Pignone controller MARK VI. The validation process should be accomplished over a larger population of test results, and probably the number of different components modelled by the virtual HazOp toolbox has to be further increased. Also, implementation of the models should be further refined in order to increase robustness and numerical efficiency of the toolbox. In particular, for an extended and efficient use of the code the integration step has to be increased to an advisable target of 10^{-3} - 10^{-2} seconds. In order to obtain this target, some simplifications and optimizations have to be introduced considering that currently the model reproduce plant bandwidth, which is far higher with respect to the dynamic behaviour measured by sensor and really controlled by industrial regulators. Regarding the future developments, it is planned an experimental campaign on a different lube oil console, in which the characterization of the thermal-hydraulic behaviour of the GE hydrodynamic journal and thrust bearings will be the main focus. In particular, in the actual implementation bearings are modelled as equivalent orifices with an assigned flow-pressure relationship which is calculated from GE NP and manufacturer data that are mainly referred to steady-state-nominal working conditions. This is a clear limit for a tool which main aim is simulation of off-design conditions and transients that may be quite far from nominal ones. The aim of this activity is the development of bearing models, which can be an advisable trade-off between numerical efficiency and the accuracy needed by a virtual HazOp analysis. At present the authors are dealing with bibliographic research and development of the corresponding simulation tools. Further research activities will also address extending the tool onto simulation of different physical domains, such as thermal pneumatics and electro-mechanical systems. In particular, the intention of the authors is to exploit the previous experience gained during simulation of railway pneumatic brakes both with commercial [14] and customized simulation codes [13] in modelling of pneumatic systems.

Acknowledgements

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