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Abstract

Hazard and operability analysis is a decisive factor to evaluate safety and reliability of plants considering the propagated effects due to consecutive failures of known critical components. A good design and analysis practice increases the robustness of the considered system in different operating conditions; however, in the plant design process, the use of a model-based design approach is fundamental to increase speed, efficiency and reliability. In this work, a tool for the 1-D simulation of thermal hydraulic plants is presented and applied to the analysis of critical system for compressor and gas turbine units, e.g. the lubrication circuits. Different from known commercial products, the proposed tool is implemented to work in cooperation with PidXP™ (the GE Nuovo Pignone P&ID definition tool), and it is optimized for fixed step solvers in order to easily include the rotating machine control logics within the simulation environment (essential prerequisite for hazard and operability evaluations). All the above makes it suitable for the fast prototyping of real time code. Moreover, the proposed tool represents a general tool in the model-based approach, and it can be used as a Simulink™ library of components that have been optimized and specifically designed in order to make easier the automatic generation of simulation models from P&Id schemes and technical documentation, reducing errors associated to data transcription and operator misbehaviour. In this work, proposed approach and test bench on experimental data for validation purposes are shown.

Keywords

Pipelines, hydraulic systems, Haz-Op analysis, RT code prototyping, fluid systems, transient behaviour

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Introduction

Mono-dimensional analysis and simulations of thermo-hydraulic systems are currently performed by several well-affirmed commercial software, such as Mentor Graphics Flowmaster™, LMS Amesim™ or Aspen Hysys, which have been validated by a wide population of users both in the academic and in the industrial fields.[1–3]

Authors, during the collaboration between the University of Florence (in particular the Mechatronics and Dynamic Modelling Lab) and the industrial partner GE Oil & Gas Nuovo Pignone (Florence, Italy), have implemented a tool (briefly named 'thermal hydraulic library (TTH Lib)') that represents an innovative trade off among different features proposed by the known commercial software and the internal specifications of GE NP procedures. The main characteristics of TTH Lib are described by the following points:

- *GE NP controller MK VI co-simulation*: GE NP uses the software and hardware in the loop (HIL-SIL) approach in the controller (MKVI) testing activities; therefore, there is a great interest to maintain the compatibility with Mathworks™

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tools, which support automatic code generation for different targets.

- *Automatic model generation*: to reduce errors introduced by data transcriptions and operator misbehaviour, the model should be automatically generated assembling a pre-defined population of sub-models using GE technical database and documentations available in the P&ID (piping and instrument diagram) drafting tool PidXP^{TM};
- *Optimization for fixed step solvers and R-T implementation*: fast prototyping of RT code involves the use of fixed step solvers to obtain a deterministic task time with pre-defined computational resources. Automatic generation of C-code for a real time target should be supported;
- *Robustness*: the tool will be used to simulate virtual hazard and operability (Haz-Op) (component failures or off-design conditions) during the design process. The tool has to be computationally robust because these critical situations often correspond to a bad numerical conditioning of the simulation parameters. The models are solved using an ODE stiffness solver, and a pre-run approach is used before the failure. This approach supposes to perform a short simulation with a reduced step-size to properly define the initial conditions.

TTH Lib description

Modelling: General principles

The general approach followed in literature,[4,5] for a mono-dimensional flow, is described in terms of mass conservation, momentum and enthalpy balances based on the following equations (1) to (3)

Table 1. Adopted symbols.

Symbol	Quantity	Unit (SI)
ρ	Density	kg/m^3
V	Volume	m^3
m	Mass	kg
t	Time	S
H	Specific enthalpy	J/m^3
P	Pressure	Pa
Q	Exchanged heat	J
T	Temperature	K
v_x	Fluid speed in axial direction	m/s
f_x	Axial tangential effort	kg m^{-2}s^{-2}
L	External work	J
Qm	Mass flow	kg/s
Qv	Volumetric flow	m^3/s
Qh	Enthalpy flow	J/s
$\xi(Re)$	Viscous friction factor	Dimensionless
β	Bulk modulus	Pa
α	Coefficient of thermal expansion	1/K
g	Gravity acceleration	9.81 ms^{-2}

(where symbols and conventions are briefly described in Table 1).

$$\frac{d\rho}{dt} = \frac{\frac{dm}{dt} - \rho\frac{dV}{dt}}{V(t)} \tag{1}$$

$$\rho\left(\frac{\partial v_x}{\partial t} + v_x\frac{\partial v_x}{\partial x}\right) = -\frac{\partial P}{\partial x} - f_x \tag{2}$$

$$dQ + \frac{dP}{\rho} = dh \tag{3}$$

In order to reproduce the dynamical behaviour of thermal hydraulic systems, partial differential equations (PDEs) (1) to (3) should be solved. Following the approach, similar to the suggested examples in literature[6–8] and usually adopted by commercial software,[9] the plant is discretized in lumped elements where the PDEs (1) to (3) are re-written in terms of control volume balances. Therefore, the system can be described by an ordinary differential equation (ODE) system where the main components are given as follows:

- Resistive and inertial (RI) element: a lumped component where only the momentum balance is implemented, in order to calculate the mass flow and the enthalpy flow. The control sections considering inlet and outlet conditions (pressure p, temperature T) are imposed by an external source or calculated by an adjacent capacitive element. If transient terms (time derivative) in (2) are neglected, only dissipative effects are modelled, and the corresponding element is called R or pure resistive element as can be seen in Figure 1.
- C (Capacitive) element: a lumped volume (or capacity) where energy and mass balances are performed to calculate a local value of T and p (assuming inlet and outlet mass Q_m, and enthalpy Q_h flows as imposed). Moreover, both the thermal and the work exchanges should be considered introducing in equations (1) and (3) and the corresponding effects as seen in Figure 1.
- T and special Junction blocks: since complex hydraulic circuits are composed by networks with several loops, hybrid elements (composed by RC elements) are used to connect multiple loops as seen in Figure 1.

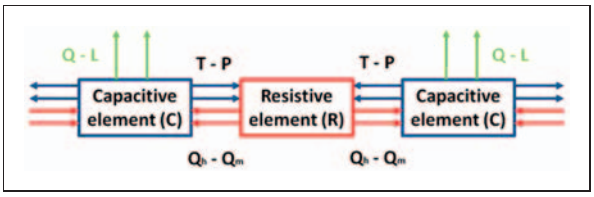

Figure 1. Example of discretization of a thermo-hydraulic plant in resistive and capacitive elements.

- 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 as seen in the example of Figure 1.

R and RI components: Sketches and equations

As seen in Figure 2, considering a uniform flow in a pipe with a constant section A, length l inclined of an angle α respect to the ground the momentum balance (2) should be re-written as (4), where Q_v is the volumetric flow (m^3/s) assumed to be homogenous along the pipe:

$$\rho l\dot{Q}_v = (p_1 - p_2)A - \xi(\mathrm{Re})\frac{\rho|Q_v|Q_v}{2A} - \rho g\sin(\alpha)Al \tag{4}$$

The term ξ represents the viscous friction factor, which is calculated as a function of Reynolds Number and of the different loss factor. In the form described by (4), the volumetric flow can be calculated by means of an integration layout schematized in Figure 3.

However, in several examples, the contribution of the time derivatives terms is negligible, and then equation (4) can be re-written in a simpler form (equation (5)) that can be solved without any additional integrator block; in this case, the element is simply called R (or 'pure resistive') and corresponds to a simpler implementation.

$$\begin{gathered}(p_1 - p_2)A - \xi(Re)\frac{\rho|Q_v|Q_v}{2A} - \rho g\sin(\alpha)Al = 0 \\ \Downarrow \\ Q_v = f(p_1, p_2)\end{gathered} \tag{5}$$

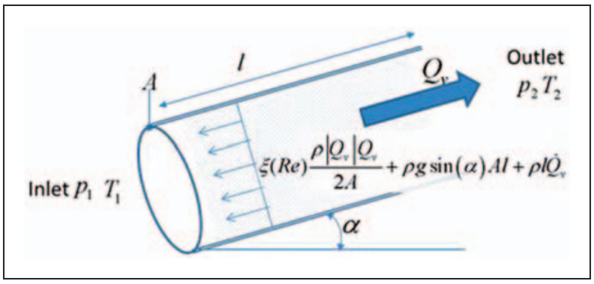

Figure 2. Sketch of a general RI element.

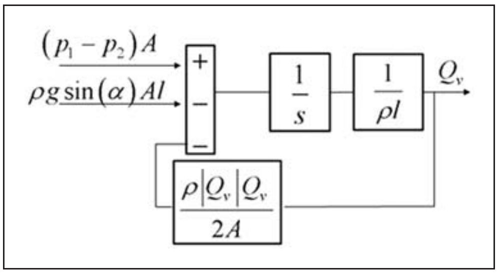

Figure 3. Simplified non-linear integration scheme of a RI component.

The mass flow Q_m is directly calculated from the volumetric flow rate Q_v and the density value of the inlet section. In addition, considering the *iso-enthalpy hypothesis* of the flow, the enthalpy flow is computed starting from the specific enthalpy.

$$Q_m = \rho Q_v; \tag{6}$$

$$Q_h = hQ_m; \tag{7}$$

The use of the R and the RI components allows the simulation of different components such as distributed or lumped pipe losses, orifices and valves, which can be defined through a variable area (flow coefficient). The controlled R components consist of R systems, which have the controller algorithm implemented using the Matlab-Simulink$^{\mathrm{TM}}$ blocks.

It is worth to note the possibility to model hydraulic actuators (such as pumps and motors) using a customized version of (5) where Q_v is directly calculated to model the actuator behaviour: e.g. a centrifugal pump is described in terms of load ϕ and ψ flow coefficients, and the (8) relation should be adopted:

$$\begin{gathered}Q_v = f(p_1, p_2, n) = f(\phi, \psi, n) \\ \phi(\psi) = \frac{Q_v}{nc_\phi}; \quad \psi = \frac{p_1 - p_2}{n^2 c_\psi}; \; n = \text{rotation speed}; \\ c_\phi, c_\varphi, \text{ characteristic coefficients}\end{gathered} \tag{8}$$

Enthalpy exchanges introduced by the hydraulic actuators have to be evaluated for the calculation of the proper enthalpy flow; indeed, the specific enthalpy h delivered in the outlet section has to be coherently recomputed taking into account the exchanged mechanical work calculated in equation (3). Even 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. The centrifugal pump-motor system is shown in Figure 4.

C components: Sketches and equations

The mass conservation equation (1) can be applied to a control volume represented in Figure 5 to determine the density ρ, and consequently, knowing that the properties of the modelled fluid are possible to calculate the corresponding pressure derivative following equation (9):

$$\frac{dp}{dt} = \beta\left[\frac{1}{\rho}\frac{\mathrm{d}\rho}{dt} + \alpha\frac{\mathrm{d}T}{dt}\right] = \beta\left[-\frac{1}{v_s}\frac{dv_s}{dt} + \alpha\frac{\mathrm{d}T}{dt}\right];$$

$$\text{with}: \left\{\begin{array}{l} \alpha = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p = \frac{1}{v_s}\left(\frac{\partial v_s}{\partial T}\right)_p \\ \beta = \frac{\rho}{\left(\frac{\partial\rho}{\partial p}\right)_T} = \frac{1}{v_s\left(\frac{\partial\rho}{\partial p}\right)_T} = \frac{-v_s}{\left(\frac{\partial v_s}{\partial p}\right)_T}; \end{array}\right. \tag{9}$$

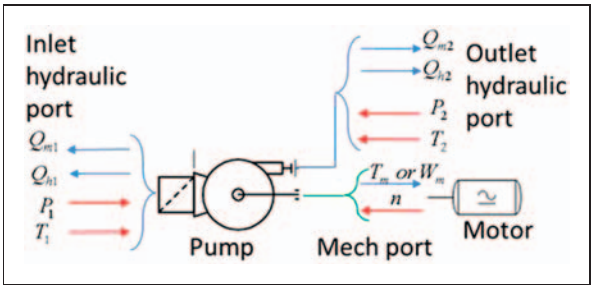

Figure 4. Centrifugal pump model and the mechanical model of the electric motor.

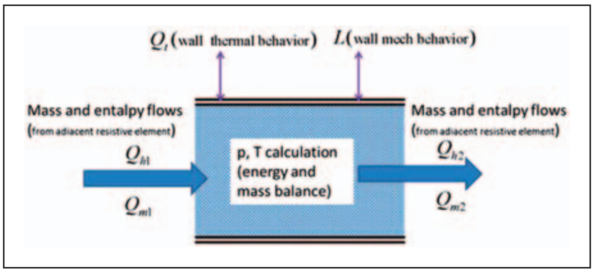

Figure 5. Control volume considered for mass and enthalpy balance.

where v_s is the specific volume (defined as the reciprocal of the fluid density ρ). Equation (9) compares the α coefficient that takes into account the thermal dilatation of the fluid.

Temperature derivative is calculated from fluid energy/enthalpy balance (3), which is re-written in the simplified form (equation (10)):

$$\frac{\mathrm{d}T}{dt} = \frac{Q_{h1} - Q_{h2} - \rho\dot{V}h + Q_T}{Vc_p} v_s + \frac{1}{c_p} T\left(\frac{\partial v_s}{\partial T}\right)_p \frac{dp}{dt}; \tag{10}$$

As a consequence of these equations, both pressure and temperature profiles are homogenous in the control volume, and they can be calculated integrating equations (9) and (10), according to the following simplified scheme (Figure 6):

The change of the volume capacity, due to the wall flexibility, is modelled through a wall function *V(p)* calculating the internal volume derivatives as function of the internal pressure coupled with the external mechanical impedance. Through this method, it is possible to model the effect of a generic real pipe wall with an elastic behaviour, or alternatively (customizing *V(p)* function), a simple effect actuator coupled with a mechanical impedance.

Also, a variable volume or pressurized tanks should be modelled as particular case of capacitive elements by properly modelling the *V(p)* function. In this case, the delivered mechanical power W_m

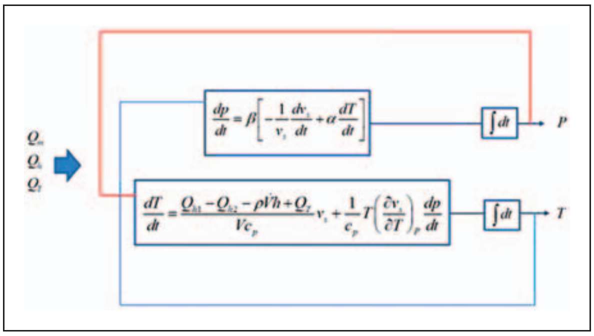

Figure 6. Simplified integration scheme of general capacitive block.

and, consequently, the work L should be calculated according to (11):

$$W_m = p\dot{V} \Rightarrow L = pdV \tag{11}$$

It is also interesting to notice that the heat exchange phenomena are modelled through capacitive blocks.

In Figure 7, a simple scheme has been reproduced that summarizes the use of different components *RI*, *R* and *C* elements to model most of the components of a thermo-hydraulic plant.

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, which are often associated to pressure-temperature working ranges where the fundamental properties of the fluids such as viscosity and density could change in an appreciable way.

In particular, in TTH Lib, the real behaviour of the fluid is modelled, considering the variability of the following coefficients as polynomial functions of fluid pressure and temperature and extrapolating the fluid properties respect to a p_{ref} and T_{ref} conditions:

- Specific volume v_s, interpolated with a second-order polynomial law:

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

- Absolute viscosity μ: approximated by an exponential law whose exponent is interpolated with a second-order polynomial law:

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

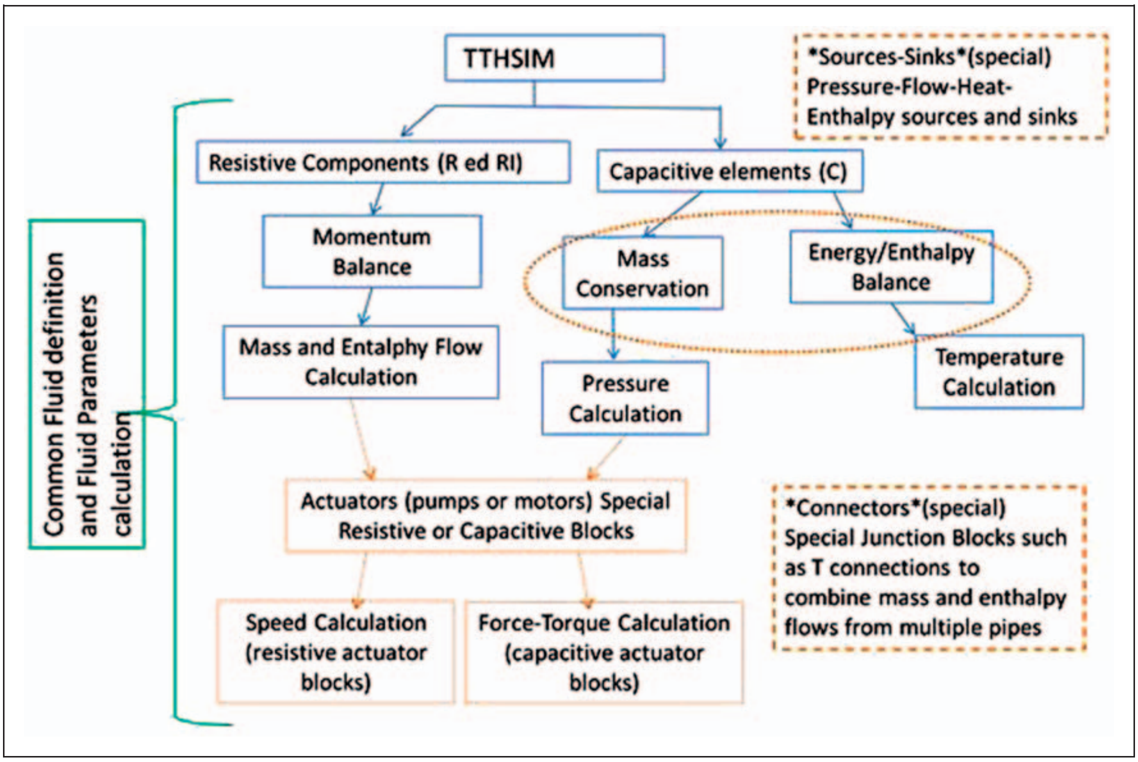

Figure 7. Simplified scheme of different elements and their usage in TTH Lib.

- Specific heat coefficient c_p: same as v_s

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

- Thermal conductivity λ: sensitivity against pressure is neglected.

$$\lambda_p = \lambda_{p0}\Big[1 + d_{t1}(T - T_{ref}) + d_{t2}(T - T_{ref})^2\Big]$$

The main advantages of the proposed approach are the simplicity of the equations, obtained using Taylor series in the linearization process and the possibility to describe in a closed form the partial derivative of P-T (which are more suitable from a computational point of view).

In Figure 8, interpolated and experimental values of ψ for diffused industrial oils are shown.

Simulink–Simscape implementation

As discussed before, a high compatibility and interoperability with internal GE models and engineering tools were a part of the product specifications; therefore, the TTH Lib tool is developed as a standard Matlab-Simulink-Simscape^{TM} library, where any lumped capacitive or resistive components are modelled as an individual block. More complex components are implemented as combination of capacitive and resistive elements, but this internal structure is transparent for the final user.

Code is optimized for RT execution, considering fixed step computation and compatibility with almost all the supported target compilers.

The typical appearance of a TTH Lib block is shown in Figure 9: each block is masked as a standard Simulink component to guarantee that the parameter customization can be managed with no need of additional know-how for a standard user. As seen in the scheme of Figure 1, implementation of a physical network using lumped RC elements involves a bi-directional data exchange between discrete capacitive and resistive lumped elements.

Mathworks^{TM} has developed its own tool for the simulation of multi-physic networks (commercially known Simscape^{TM}), and the bi-directional data exchange between blocks is performed using customized Simscape signals. In this way, it is also assured a complete compatibility between TTH Lib and the corresponding Multi-physics tools of Mathworks (also including solvers optimized for the simulation of physical networks). The command signals or the access to internal states of the component are implemented as standard Simulink Input–Output port; the typical aspect of a block is represented in Figure 9. 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 (piping and instrument diagram), mostly derived from ISA standard S5.1 Instrumentation Symbol Specifications.

In particular, to perform Virtual Haz-Op in each block, there are also defined parameters and dynamical inputs to control the failure state of the component to partially automate the simulation of sequential or multiple failure states.

Lumped pipe models

Also, pipes are modelled using lumped *RI*, *R* and *C* components, and different kinds of pipe models should be used according to the level of required accuracy. Different pipe sub-models are available, i.e. multiple *C–R* or *C–RI* components are usable. As default, pipe connections are generated using the simpler pipe model compatible with the adjacent connected elements (Figure 10).

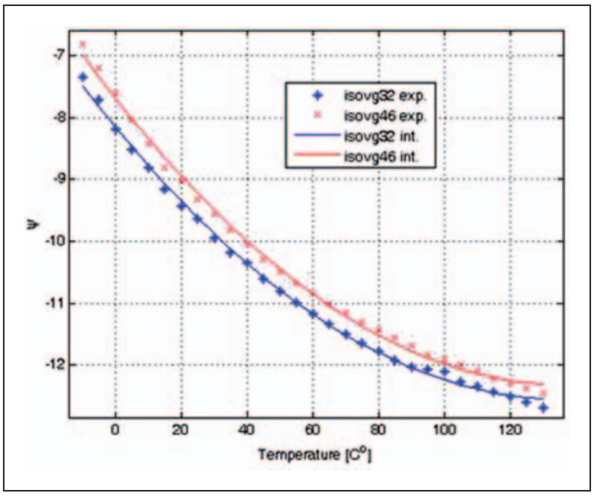

Figure 8. Experimental and interpolated behaviour of logarithmic viscosity coefficient ψ respect to temperature.

Automatic model generation

In order to reduce errors and delays due to model transcription and data transcription from technical documentation, the Simulink model can be automatically generated by P&Id schemes taken from GE PidXP configuration tool (an engineering tool/database for the definition and sketch of hydraulic systems).

Using a simple tool internally developed by GE, the user is able to automatically extract a network topology from a P&Id scheme of the hydraulic system, where each component is associated to the corresponding database of properties and technical information and allows the automatic generation of the TTH Lib model using remote construction instructions. The topology of the automatically generated model is very similar to the P&Id scheme since there is 1:1 correspondence among P&Id symbols and TTH Lib 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, considering that most of the parameters are masked, and the blocks are accessible as standard masked subsystem.

The failure list is automatically created starting from the elements present in the plant topology; each component has several failure modes depending on the element characteristics (e.g. the three-way valve

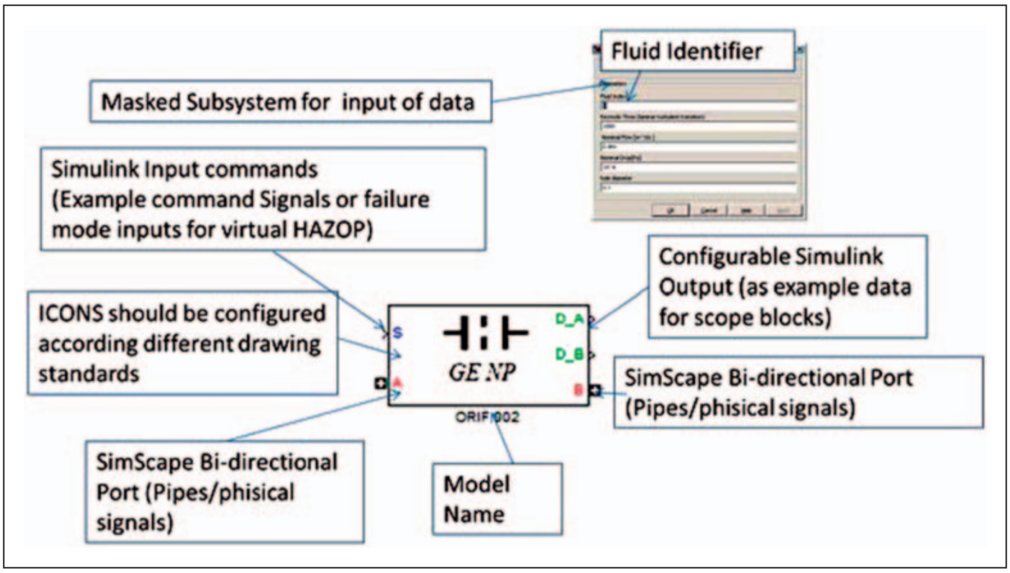

Figure 9. An example of TTH Lib simulation block (a flanged orifice) with corresponding conventions adopted for data-exchange ports.

(TCV) can failure remaining open both in the hot side and in the cold one). The failure modes are defined according with the experience and the know-how of the GE NP technicians.

The workflow corresponding to Automatic Model Generation from GE NP PidXP is schematized in Figure 11.

In Figure 12 is represented the GUI developed for GE Nuovo Pignone where the main parts used in the virtual Haz-Op analysis are defined (according with GE NP requirements). The GUI consists of four parts: the first part contains the P&Id scheme and the block set list, the second part (Human Machine Interface) allows the simulation of the Lube console model in different situations, the third part (Virtual Haz-Op) defines the list of failures and the start-time of the failure and, finally, the fourth part (Post Processing) shows the results of the virtual Haz-Op analysis, which can be also saved or exported.

It is interesting to notice that the software is designed with a modular approach, and so an expert user may directly drop, block to produce its 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 reduces the risk of human errors and assures a safe and repeatable way of working.

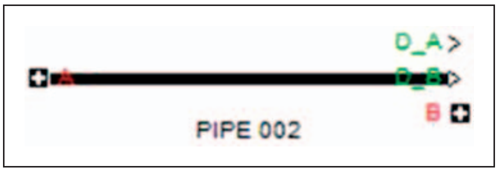

Figure 10. Appearance of a standard pipe model.

Optimizing integration and solving methods

The TTH Lib 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, and some considerations should be done.

Simulations of thermo-hydraulic systems (and more generally of multi-physics systems) involve numerical troubles:

- *Numerical stiffness*: associated, as for example, to the rigid behaviour of the fluid (which is near to uncompressible).
- *Non-linear behaviour*: a hydraulic plant is composed by elements with highly non-linear behaviour, which often produces strong discontinuities in the shape of the calculated solutions.
- *Mixed differential algebraic equations and ordinary differential equations:* combinations of both differential algebraic equations (DAE) and ordinary differential equations (ODE) equations involve the use of a very robust solver.

Since the feasibility of RT simulation plays an important role of the tool specifications, authors have optimized the code in order to privilege robustness when used with fixed step solvers and limited computational resources, which involve the use of low sampling-solving frequencies.

For these kinds of applications, implicit solvers proved to be more stable than the explicit ones; in particular, the *ode14x*[10] is an extrapolation solver

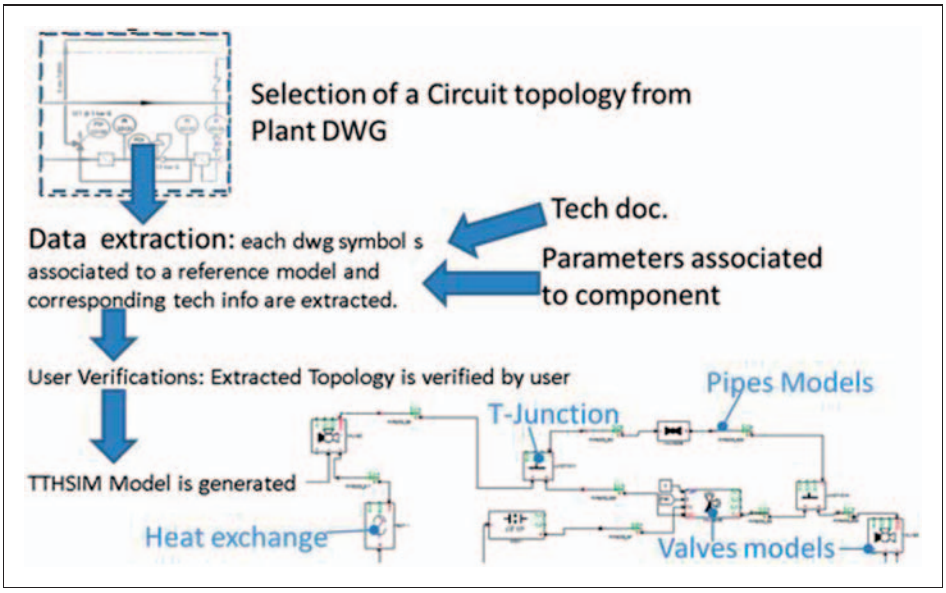

Figure 11. Typical workflow from GE P&Id scheme to the corresponding TTH Lib model.

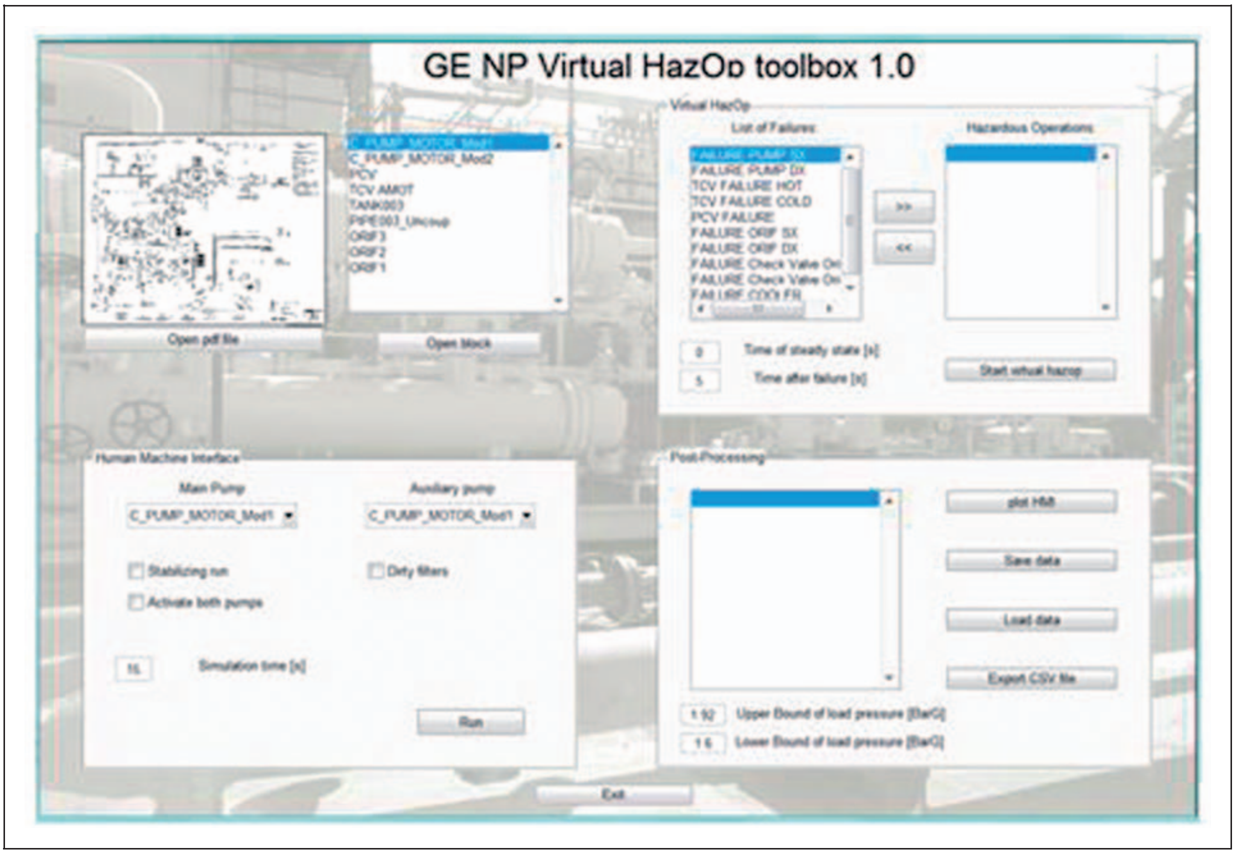

Figure 12. The developed GUI for GE Nuovo Pignone.

based on linearly implicit Euler method,[11,12] and has been preferred because it represents the best compromise in terms of stability and numerical efficiency.

Also, a pre-simulation or stabilizing run should be 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 Haz-Op analysis, where it is required to perform long or multiple simulation patterns in which different or worst case scenario have to be analysed; even in this case, the stability represents a hard issue since the simulation of 'stressed' plants often involves the implementation of bad conditioned physical systems operating in a situation, which is quite far from the nominal one.

In this case, implicit solvers have proved to be a better compromise between performance and stability. However, it is given to the user with the possibility to associate the application of a failure scenario to a change of integrator parameters, splitting an analysis in a sequence of coherent simulations with different solving tolerances: more relaxed for time-consuming situations and more demanding from 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 produce a critical effect.

Preliminary cross-validation and debugging

The proposed tool has been built from equations described in the previous paragraphs. The debugging and the validation phases are a quite onerous task, which can be preliminarily 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 ongoing but preliminary results are encouraging.

Cross-validation with an existing commercial software

A preliminary debug of the code is performed comparing the results obtained by TTH Lib and a commercial code on simplified benchmark models (starting from elementary components to simplified scenarios, which are considered meaningful 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.

Since some components may be not implemented or differently implemented, on the commercial code, coherence between the two models is carefully verified.

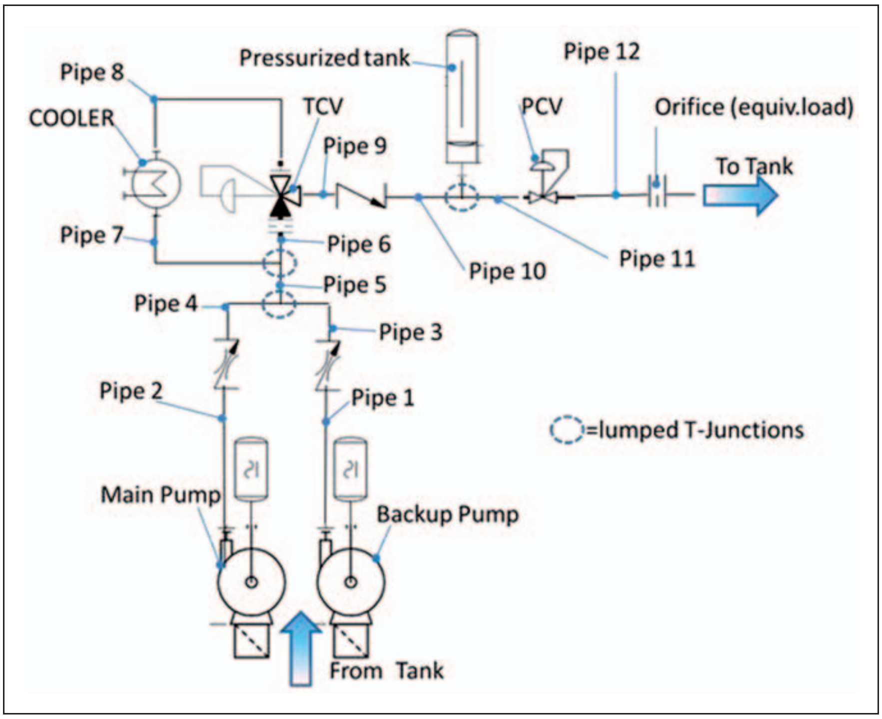

Figure 13. Simplified plant scheme.

Among the various tests performed, in this work, the authors are focused on the plant described in Figure 13.

The hydraulic load, i.e. the bearings of a turbomachine, is modelled as an equivalent orifice (load in Figure 13), and it has to be fed with an assigned inlet pressure. The inlet pressure is self-regulated by a pressure regulator valve ((PCV) in the scheme). 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 available.

Asynchronous motor is modelled considering a known-tabulated speed-torque response $T_e(n)$ as seen in Figure 14, and a filtering transfer function is introduced to model inertial and viscous friction mechanical loads (equation (11)).

$$T_e(n) - T_m = J_m \dot{n} + fn \Rightarrow n = \frac{T_e(n) - T_m}{J_m s + f}$$
$$J_m = \text{mech.inertia}; \quad f = \text{friction factor} \tag{12}$$

During the failure of the pump, the pressure of the PCV is stabilized by the pressurized tank (called PT).

A TCV is used to stabilize oil temperature to an assigned value of 60 °C self-regulating the volumetric flow passing through a cooler (modelled as a composite R–C–R resistive, capacitive component). The cooler is simulated using a thermal model in which a constant heat exchange coefficient is supposed.

Additional orifices and check valves are added to the plant to simulate other known lumped losses. Pipes are modelled as R–C–R elements (two resistive and capacitive elements) neglecting the contribution of inertial forces in equations (Tables 2 and 3).

Using the simplified model described above, different failure or operating conditions can be simulated; in particular, the following scenario is proposed:

- At the beginning of the simulation, the main pump is activated, and then after few seconds, it is suddenly cut off, simulating, i.e. the opening of an electric protection of the corresponding motor.
- Backup pump is re-activated considering a variable delay ranging from 0 to 20 s, and the start-up transient, due to electrical and mechanical behaviours, is completely simulated.
- The effects on the controlled load are evaluated considering different pressure tank sizes.

In Figure 14, inlet mass flow calculated considering different delays in the activation of the backup pump is considered: the results obtained with commercial software and the proposed tool substantially agree considering some implementation differences that cannot be removed since the implementation of the commercial software cannot be completely known or accessible to University users. Same considerations can be also performed considering the pressure of the tank or temperature of the fluid in the outlet section of the PCV considering the dynamic response of the TCV valve (as can be seen in Figures 15 to17).

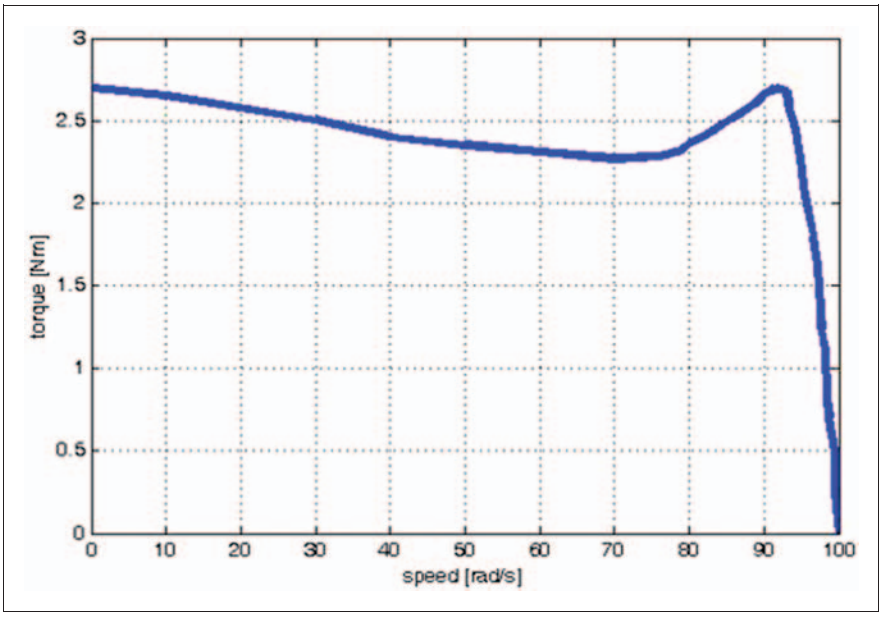

Figure 14. Tabulated torque speed curve of the asynchronous motor.

Table 2. Pipe parameters.

Pipe N. (model)	Length (m), diameter (mm), exchange coefficient ($JK^{-1}m^{-2}$)	Init. conditions $Q_v(0)$ (m^3/s), $T(0)$ (°C)
1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12 (C)	3100.0	0.70
9 (C–R–C–R–C)[a]	9100.0	0.70

[a]Additional losses equivalent to an equivalent orifices of 20 mm are added.

Moreover, to establish the preliminary estimation of efficiency of the implemented code, the running times of both codes are compared considering fixed and variable step implementation as seen in Table 4.

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 TTH Lib because the simulation performances are heavily affected by the simulated scenario.

Considering a 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. 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 10 times smaller.

The corresponding difference in terms of global duration of the simulation is much lower (about 40%), and this result is only partially justified by the different kinds of solver adopted. Further efforts have to be performed to increase the efficiency of the code and to perform a smarter implementation because proposed code is still much slower in terms of turn-around time, intending with turn-around time the time required to solve a single integration step.

Calculation of computational times is performed considering a standard notebook with Intel™ i7core processor and 8 GB of RAM with a Microsoft Windows 7 operating system. For Matlab-Simulink, implementation is considered the use of an *Rsim* target (a generic non-real time target, which is used to produce a standalone executable of the code). In this way, it is also possible to verify the possibility of automatically compiling the TTH Lib code to generate a standard executable for a generic target.

Preliminary validation tests: Lube oil console

The benchmark case, proposed by GE NP, is 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 in accordance with the GE NP plant designers simulate the bearings as an equivalent orifice described by means of a GE NP formula.

The objective of this benchmark case is the study, during the plant design phase, of the effects of the presence of a gas tank in the circuit during the Haz-Op phase. Usually, the gas tank is used to prevent damages during the transient phase or when some component failures happen. The presence of the gas tank involves a further complexity in the plant and a high economic investment.

Table 3. Component parameters.

Component	Parameters	Initial conditions $Q_v(0)$ (m^3/s), $T(0)$ (°C)
Check valve	0.011 m^3/s ($\Delta P = 1$ Bar)	0.70
Check valve with orifice	0.011 m^3/s ($\Delta P = 1$ Bar) orifice diameter (3 mm)	0.70
PCV	ϕ55 mm (full open) pressure set-point = 2.5 Bar	0.70
Pressurized tank	0.2 m^3 (volume) 2.72 Bar (pre-charge)	0.70
TCV	ϕ35 mm (full open) temperature set-point = 58°C	0.70
Heater	ϕ35 mm, 7850 WK^{-1}	0.70

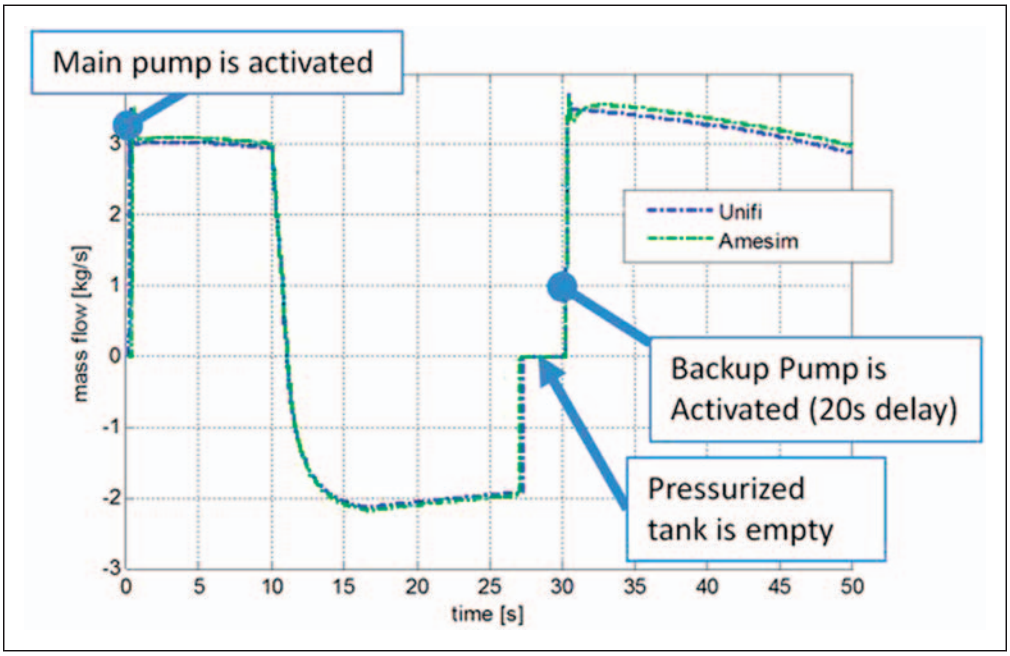

Figure 15. Comparison of the inlet mass flow of the pressurized tank considering different time delays in the activation of the backup pump from 0 to 20 s.

The validation test of the TTH Lib models and the Virtual Haz-Op tool has been performed comparing the results of the simulation model with the experimental results provided by GE NP.

Therefore, the aim of the test is to verify the capability of the tool to simulate in a near to realistic way a typical flow-pressure transient in which a relatively fast dynamic behaviour has to be reproduced.

The simulation model is obtained using the automatic generation of dynamic model starting from the P&Id scheme.

The lube oil console can be schematized into the model represented in Figure 18, and the parameters are described in Tables 5 and 6:

The test analysed in this paragraph is carried out during the String Test performed by GE Nuovo Pignone in the Massa site, and it is related to main pump failure. Indeed, it is necessary to analyse the pressure and the mass flow in the equivalent load during the start-up of the backup pump (pressure transient analysis). Moreover, since the simulation model carries out a thermal-hydraulic analysis, a comparison between the temperatures measured after the TCV is evaluated (temperature transient analysis).

The lube oil console model is connected with the GE NP controller (MKVI), where all the alarm logics and the controller actions are implemented. The model of the controller MKVI is directly supplied by GE NP. In this way, a SIL analysis can be performed, and the same simulation model could be also used both for the model-based design and the controller testing.

In particular, the following failure sequence is simulated:

- main pump is switched on, and the pressure on all the plant sections is stabilized at their nominal steady-state value.

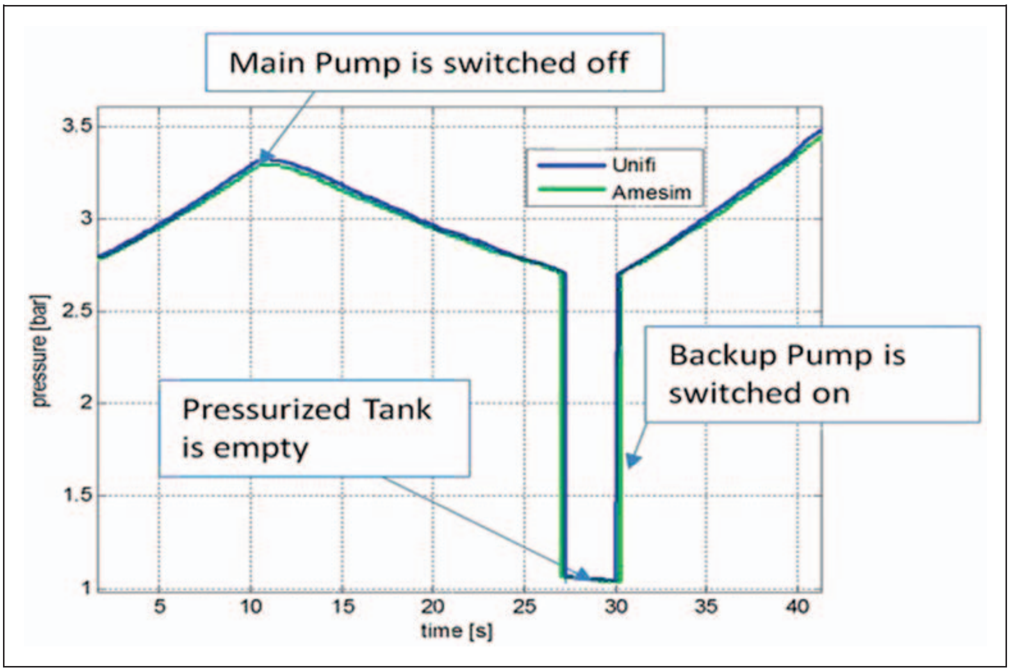

Figure 16. Pressure inside the pressurized tank, comparison between commercial software (LMS AMEsim) and the tool TTH Lib (considering a 20 s of delay in the activation of the backup pump).

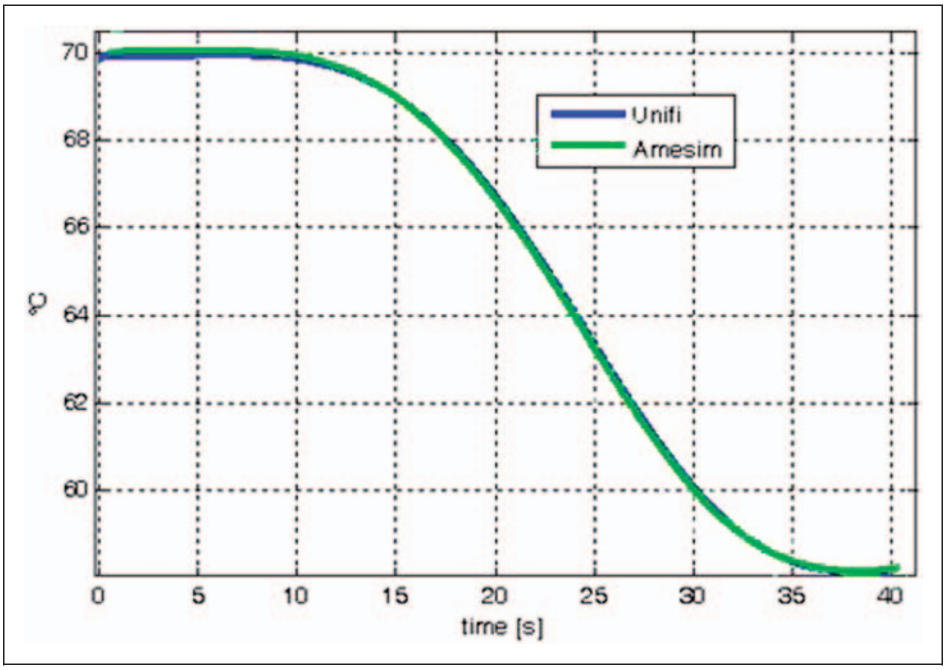

Figure 17. Temperature in the outlet section of the PCV (No delay in the activation of the backup pump).

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

Tool	Solver (order)	Solver step(s)	Execution time (s)
TTH Lib	'ode14x'	10^{-4}	174
Commercial	Euler	$10^{-5} - 10^{-6a}$	290 (minimum)
Commercial	Adams-Bashforth (2)	$2 \times 10^{-5} - 10^{-6a}$	285 (minimum)
Commercial	Runge-Kutta (2)	$2 \times 10^{-5} - 10^{-6a}$	275 (minimum)

[a]Stability troubles, by lowering components dynamics the same simulations should be repeated dividing integration step of one tenth however the performance ratio does not change.

- main pump failure is simulated by suddenly switching off the component.
- as the collector pressure measured by the MKVI controller falls under an assigned value, the backup pump is switched on.

The points of interests that are acquired by the proper sensors and transmitted to the MKVI controller, highlighted by a red point into Figure 18 are the following ones:

- The *load pressure*: the pressure measured in the section ahead the equivalent orifice (which represents the bearings).

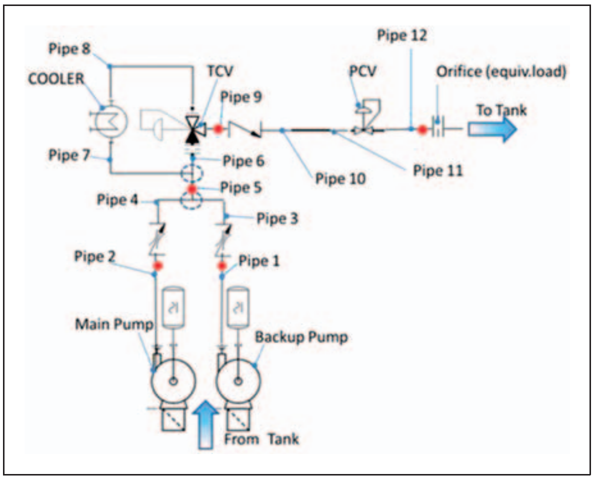

Figure 18. Sensors in the lube oil circuit.

Table 5. Pipe parameters.

Pipe N. (model)	Length (m), diameter (mm), exchange coefficient (JK^{-1}m^{-2}]	Initial conditions $Q_v(0)$ (m^3/s), $T(0)$ (°C)
1, 2, 3, 4, 5, 6, 7, 8, 10 (C)	3150.0	0.43
Vertical pipe[a]	7150.0	0.43

[a]Additional losses equivalent to simulate 7 m of vertical load are added.

- The *main pump pressure* and the *backup pump pressure*.
- The *collector pressure*: it is the pressure measured in the T-Junction after the two pumps, the main and the auxiliary pump.
- The *regulated temperature*: it is the temperature measured after the TCV.

Every simulated signal is applied a first-order low pass filter (equation (13)), which reproduces the dynamic behaviour of the pressure transmitter and of the integrated signal conditioning used on the plant to which are referred the experimental data.

$$y(s) = \frac{1}{1+\tau s} \quad \text{where} \quad \tau \approx 0.4s \tag{13}$$

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, also implemented in Matlab in order to automate the process.

The graph corresponding to the structure of the proposed simulator is shown in Figure 19.

Results of the validation process: Pressure transient analysis

The validation is carried out by comparing measured pressure profiles with the corresponding ones

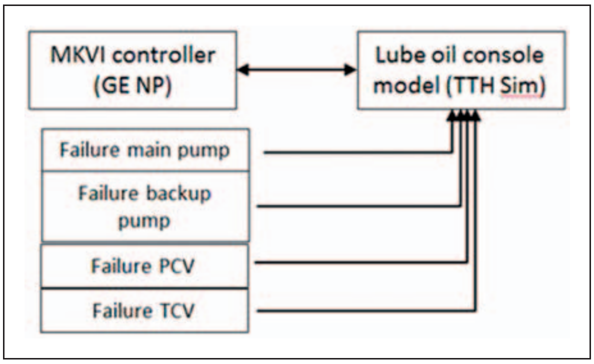

Figure 19. Interactions between the Lube oil console, the model of MKVI controller and the failure blocksets.

Table 6. Component parameters.

Component	Parameters	Initial conditions $Q_v(0)$ (m^3/s), $T(0)$ (°C)
Check valve	0.011 m^3/s ($\Delta P = 1$ Bar)	0.43
Check valve with orifice	0.011 m^3/s ($\Delta P = 1$ Bar) orifice diameter (3 mm)	0.43
PCV	$C_v = 125$ and set point pressure = 3.5 Bar A	0.43
TCV	$C_v = 270$ and temperature set-point = 50°C	0.43
Heater	ϕ35 mm, 7850 WK^{-1}	0.43

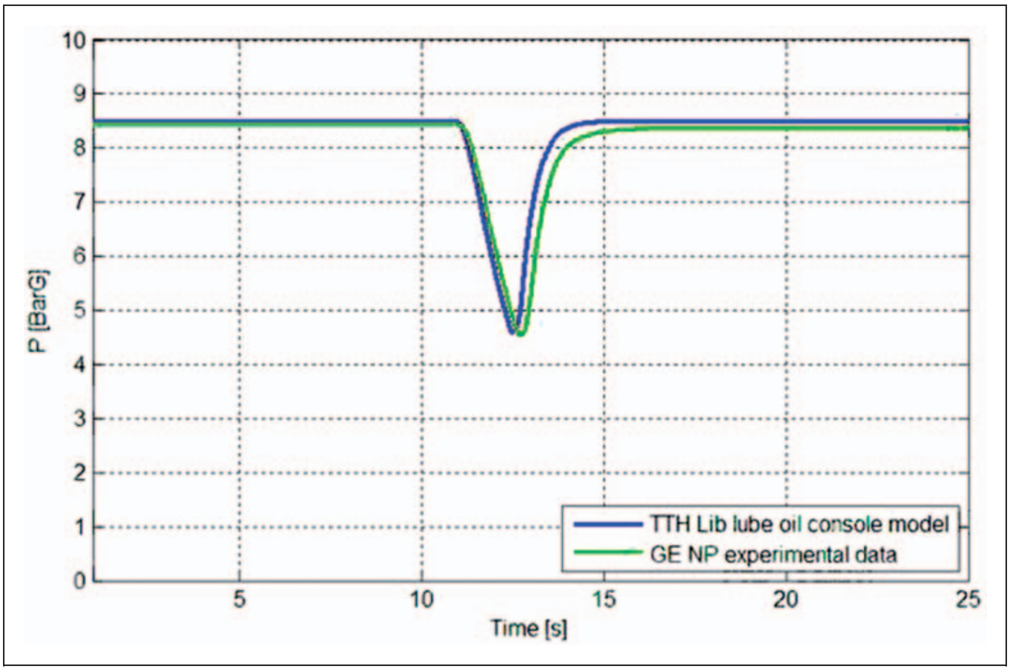

Figure 20. Collector pressures.

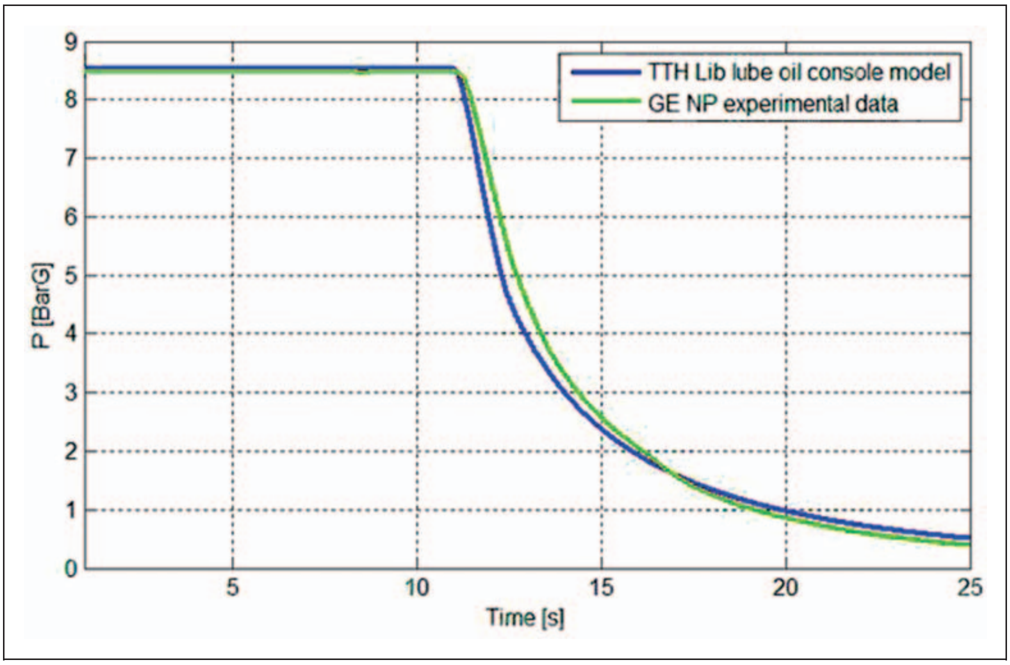

Figure 21. Main pump pressures.

Table 7. Maximum errors.

Transmitter	Relative error (%)
Collector pressure	5
Main pump pressure	15
Auxiliary pump pressure	10
Load pressure	5

calculated using the Virtual Haz-Op tool based on the TTH Lib models.

Referring to the scheme of Figure 18, in Figure 20, the comparison between the simulation model and the experimental data of the collector pressure is shown. The behaviour of the measured and the calculated pressure is quite similar, also considering the uncertainties on component parameters: as shown

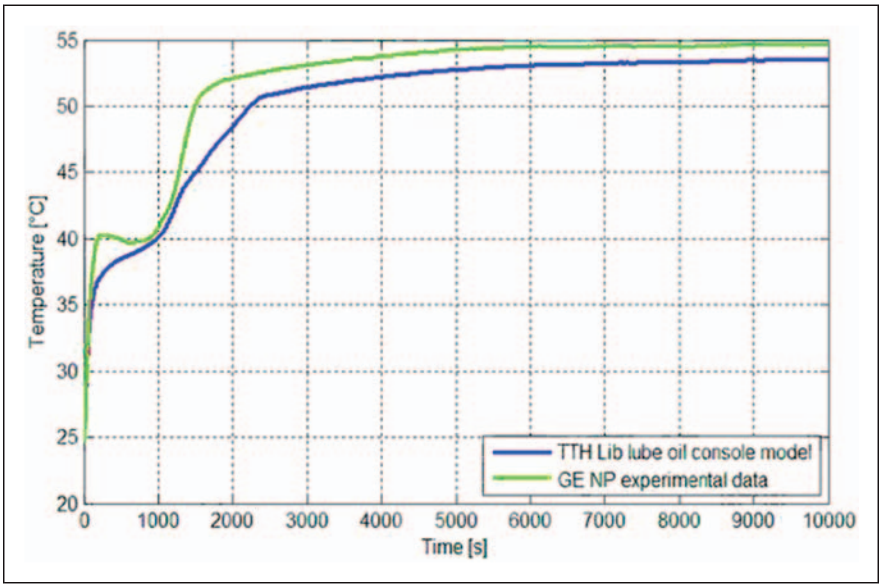

Figure 22. Comparison between the experimental and the simulated data starting from 25 °C.

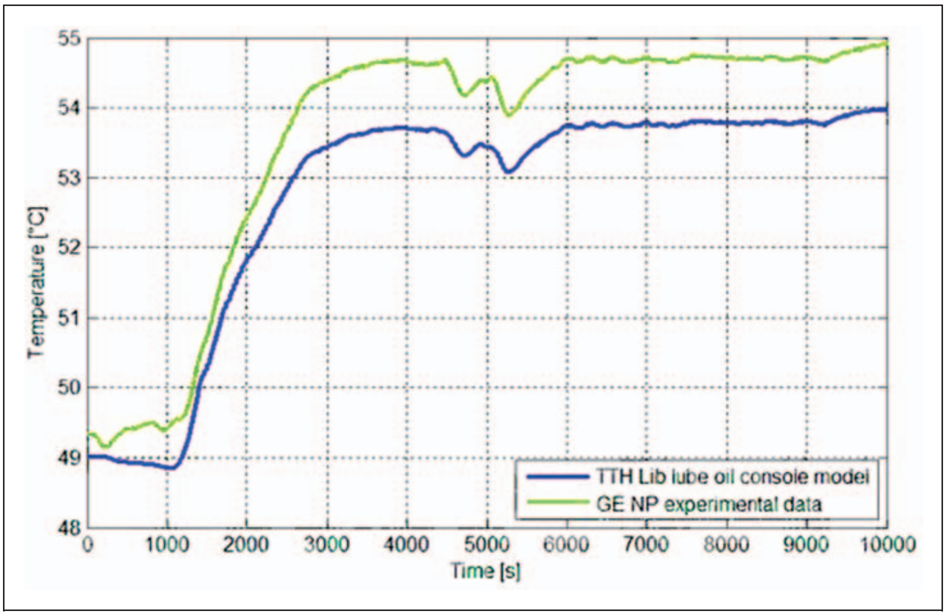

Figure 23. Comparison between the experimental and the simulated data starting from 49 °C.

in Figure 20, an offset is clearly recognizable between the experimental, and the simulated data probably are caused by an offset in the sensor.

In Figure 21 is represented the dynamical behaviour of the main pump after the failure: the pressures decrease through the same curve, which implies that the resistance of the plant is nearly the same (Table 7).

As can be seen from the presented results, the dynamical behaviour of the lube oil console model and the lube oil console experimental data is very similar; probably, the main differences depend on both an approximation of the sensor transfer functions and the complexity of the system.

Results of the validation process: Temperature transient analysis

The validation process analyses even the temperature transient measured by the temperature sensor after the TCV. The temperature transient is longer than the pressure transient due to the thermal inertia of the oil. The TCV is a three-way self-regulated

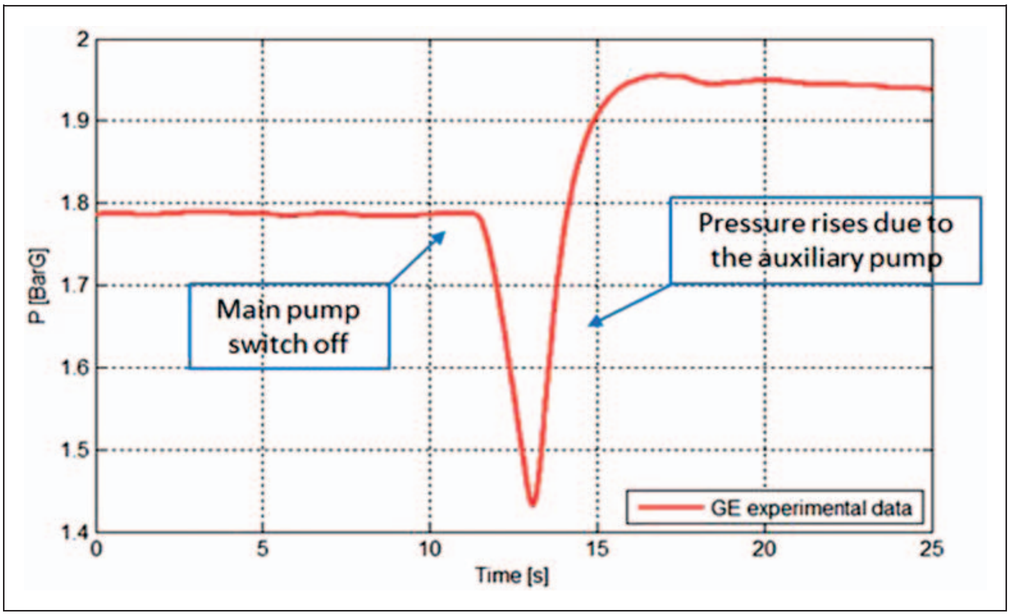

Figure 24. Trend of the load pressure during the pump switch.

valve with a hot entry and a cold entry. The TCV is modelled thanks to the datasheet parameters and GE NP plant engineers. The data are related to the previous String Test and provide two different starting situations: the first starts by the environment temperature (about 25 °C), while the second starts by a temperature about 49 °C due to the pre-heaters intervention.

The set temperature of both tests is 55 °C.

In Figure 22, it is worth to note the dynamical behaviour of the temperature transient characterized by a fast heating caused by the pre-heater in the lube oil tank; then there is a modulation by the TCV between the hot and cold entries to obtain the set temperature (55 °C). The steady state is near the set temperature probably due to the offset and the hysteresis of the valve and the offset of the sensor.

In Figure 23, starting by a pre-heated plant, it is possible to see the transient due only to the TCV modulation; indeed, in this graph the offset and the hysteretic behaviour of the valve are clearly visible.

Even in this case, as can be seen from these figures, the experimental data and the TTH Lib lube oil console model are quite similar. The main differences are certainly caused by the uncertainties of cooler parameters; in addition, there is an approximation of the sensor transfer functions.

Conclusions and future developments

In conclusion, during this work, the authors have implemented in Matlab-Simulink, a TTH Lib that was first compared with the commercial software (Amesim) to evaluate the physical behaviour. After that, a procedure has been implemented to automatically convert the P&Id scheme of GE NP into the proper TTH Lib dynamical model. In addition, a software to the virtual Haz-Op analysis with a GUI is deployed to the GE Nuovo Pignone.

The benchmark case proposed by the industrial partner GE NP is a mineral lube oil console that is used to guarantee the desired pressure and flow to the auxiliary systems of a compressor plant.

Finally, the authors performed a Virtual Haz-Op using the lube oil console model and compared these results with the experimental data provided by GE NP on the real lube oil console. The data acquired by GE NP on a real String Test showed both the pressure transient during a pump switch off and the temperature transient during the start-up of the plant. The results highlighted in the previous scenarios confirmed the preliminary studies of the authors. Indeed, as can be seen from Figures 20, 21 and from table, the physical behaviour of the first part of the oil circuits agrees among the experimental and the numerical results.

In addition, the use of the Virtual Haz-Op toolbox, during the plant design phase was useful to analyse the behaviour of the plant and to decide to eliminate the gas tank from the circuit. In fact, through a virtual analysis of the plant, it was possible to treat all the failures, and the pump switch off transient in order to verify the load pressure would remain over the trip alarm (about 1.2 BarG) with the PCV and MKVI controller interventions only (Figure 24).

The collaboration between the University of Florence (in particular the Mechatronics and Dynamical Modelling Laboratory) and the GE Nuovo Pignone has carried out a thermal-hydraulic library in Matlab-Simulink environment to perform SIL–HIL analysis and a software ('virtual Haz-Op toolbox') to realize, during the plant design, a preventive Haz-Op analysis. The use of this software during the plant design has permitted to eliminate several components, in particular the gas tank, and the effects pre-evaluated by the software have been confirmed during the String Test presented in Chapter IV.

The further developments of this activity will be the analysis of several lube oil consoles provided by GE NP and also the characterization of the thermal–hydraulic behaviour of the GE hydrodynamic journal and thrust bearings.

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, which are mainly referred to steady-state-nominal working conditions. This is a clear limit for a tool whose main aim is the simulation of off-design conditions and transients, which may be quite far with respect to nominal ones.

Therefore, the authors are developing the concept of using finite element simulation and simplified models (taken from literature and tuned on a reduced set of expression data) to produce rough models that are able to extrapolate approximately the behaviour for limited variations of bearing working conditions.

The main advantage of this approach should be the limited numerical resources and the fast response of the proposed models. Currently, the authors are dealing with bibliographic research and developing of the corresponding simulation tools.

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