Convergence behaviour of coupled pressure and thermal networks

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Summary: A new concept of the coupling between pressure and thermal networks for thermal simulations of power devices is presented. The solution method and the convergence behaviour are discussed.

1 Introduction

The network approach is traditionally used for thermal simulations of electric power devices. In particular the coupling between thermal and pressure network seems to offer a good alternative to the mesh based methods like CFD thanks to an acceptable accuracy and a moderate computational effort. However, the first attempts to couple both network types have shown that the convergence behaviour is a limiting factor [1]. In this paper we present a new concept of the coupling between thermal and pressure networks as well as results of our investigations to mitigate the convergence problems.

2 Network concept

Let us consider a power transformer represented as a simple thermal model, Fig 1a. It consists of a coil submerged in a fluid as a heating device and a radiator as a cooling device dissipating heat to the ambient air. The circulation of the fluid through the coil and the radiator keeps the temperature of the coil within the required limit. The flow of the fluid determines the topology of the extended pressure network shown in Fig. 1b. Each “fluid flow” branch (red, thick line in the middle) is assisted by two “temperature” branches (thin, green lines) that enable propagation of the fluid temperature along the network according to the computed direction of the flow. The mixing of the fluid at different temperatures is performed by the “mixing nodes”. The coupling to the thermal network is realized by the “thermal junction” element. This element creates a temperature jump $\Delta\vartheta$ in the corresponding temperature branch, which is determined by the mass flow rate $\dot{m}$ in this branch and the power P flowing from/to the thermal network via the “fluid node”:

$$P = \dot{m} c_p \Delta\vartheta \qquad (1)$$

where c_p is the specific heat of the fluid. The formula (1) is also used as a basic equation in implementation of the “mixing nodes”.
The “fluid nodes” provide a galvanic connection to the thermal network, which is partially shown in Fig. 1c. The resistors used in the network schemes (Fig. 1bc) are formulated according to thermodynamic similarity theory [2] and will be explained in the extended version of this paper.

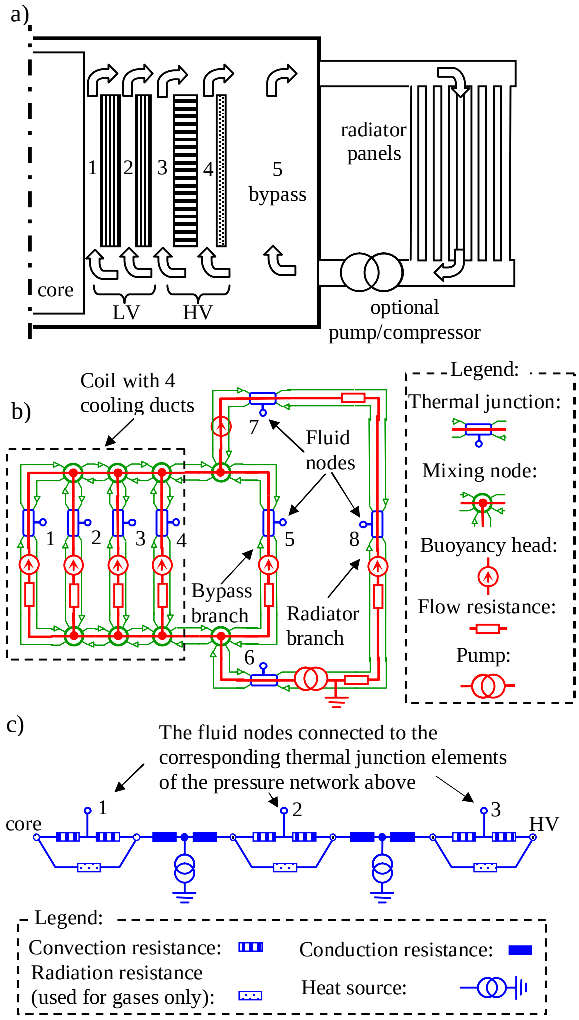

Fig. 1 a) Transformer coil and radiator as a thermal model, b) the corresponding extended pressure network, c) part of the thermal network (for 2 inner LV solid segments of the coil and adjacent ducts)

Table 1 Analogy between quantities and units of electric, thermal and pressure networks.

Electric network	Thermal network	Extended pressure network	
		Temperature branches	Fluid flow branches
Current [A]	Power [W]	- *)	Mass flow rate [kg/s]
Voltage U [V]	Temperature [°C]	Temperature [°C]	Pressure [Pa]
Electric resistance [Ohm]	Thermal resistance [K/W]	- *)	Flow resistance [1/(m*s)]

*) There is no "current" in the temperature branches of the pressure network. These branches transfer the "temperature signal" only. The direction of this transfer is the same as the direction of the fluid flow.

3 Solution method

In order to obtain a stable solution of the coupled networks we applied 3 following techniques:

a) Separation of fluid flow branches from thermal/temperature branches
b) Adaptive relaxation
c) Control of the flow direction change

Ad a): The coupled network problems are difficult to solve using the Newton-Raphson method implemented by Spice. Therefore, we have split the coupled network into 2 separate networks and solve them iteratively. The first network, pure pressure one, consists of the fluid flow branches including all flow resistances, buoyancy heads and pumps. The second one consists of the whole thermal network and the temperature branches of the extended pressure network. The "thermal junction" and the "mixing node" elements are the only network components that have a separate representation dedicated for each of the both networks. The separated networks can be solved using Spice by assuming boundary conditions in form of interface variables that are iteratively delivered by the solution of the other network. These interface variables include mass flow rates and velocities as a solution of the pure pressure network as well as temperatures as a solution of the thermal/temperature network.

Ad b): A relaxation technique is needed to ensure the convergence. The actual values of the interface variables are modified in such a way that the difference between subsequent iterations is adaptively reduced from 80 % (for the first iteration) up to 1 % (for higher iteration counts).

Ad c): The network branches with a small mass flow rate show a tendency to change the flow direction during the iterative solution. Due to the significant temperature difference between the top and bottom fluid the direction changes may lead to non-convergence. For the vertical coil ducts this problem can be mitigated by disabling the flow from the top to the bottom by means of "blocking" resistors. In case of branches for which the flow can be bidirectional an enhanced relaxation technique has to be applied.

4 Result

An example of the convergence behaviour has been presented in Fig. 2. It shows the mass flow rate within a coil duct of a liquid type power transformer. We selected a duct transporting a relatively small fraction of the total heat power (<0.5 %). Consequently we need 49 iterations to achieve the convergence criterion (<= 0.001 relative change). Other load cases of the same transformer with larger or zero heat power transported through the same duct converge within 10-20 iterations. The typical solution time on a standard computer is in the range of 0.5 s.

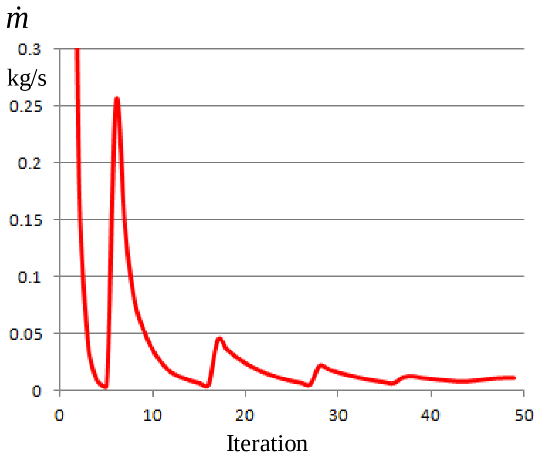

Fig. 2 Example of a convergence curve for mass flow rate in a transformer coil duct

References

[1] Gramsch C., Blaszczyk A., Löbl H., and Grossmann S., *Thermal Network Method in the Design of Power Equipment.* Springer Verlag, Heidelberg, SCEE Conference Book 2007 (ISBN 978-3-540-71979-3).

[2] Rohsenow W. M., Hartnett J. P., and Cho, Y. I. (Eds.), 1998, *Handbook of Heat Transfer*, McGraw-Hill, New York.