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Energetic Macroscopic Representation of a linear reciprocating compressor model

Mahbod Heidari [a,*], *Sébastien Wasterlain* [a], *Philippe Barrade* [a], *François Gallaire* [b], *Alfred Rufer* [a]

[a] LEI, STI, EPFL, Lausanne, Switzerland
[b] LFMI, STI, EPFL, Lausanne, Switzerland

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ABSTRACT

This article introduces the energetic macroscopic representation (EMR) as approach for the dynamic nonlinear modeling of a reciprocating air compressor. EMR has been introduced recently for research development in complex electromechanical systems and is based on action reaction principle. The compressor is divided into simple subsystems including: driver mechanism, cylinder head, valves and reservoir. Models are developed for different subsystems, which are assembled into a final overall system EMR. Since the final application of this model will be an isothermal Compressed Air Energy Storage system (CAES), special attention has been paid to transient heat transfer considering the thermal resistor and capacitor effect of the walls adopting a thermoelectric analogy. The results were verified both using Finite Element method and experiment. The EMR modeling presented here allows the modeling of multi-physics components and highlights the interactions of the electromechanical, heat transfer and fluid mechanics phenomena that occur simultaneously in an air compressor.

Représentation énergétique macroscopique d'un modèle de compresseur linéaire à piston

Mots clés : Compresseur à piston ; Transfert de chaleur ; Representation énergétique macroscopique ; Analogie thermoélectrique ; Réservoir

1. Introduction

Reciprocating compressor is one the most important machines used throughout various industries. Due to its importance considerable effort has been devoted by many researchers toward the development of mathematical models for computer simulation of this type of machine. In general, a cycle of operation of a high speed positive displacement compressor can be described as a number of complicated phenomena, interacting and taking place in a short period of time.

* *Corresponding author*. Tel.: +41 21 693 47 89; fax: +41 21 693 26 00.
E-mail address: mahbod.heidari@epfl.ch (M. Heidari).
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Nomenclature

m	Mass (kg)
$\dot{m}$	Mass flow ($kg\ s^{-1}$)
$\dot{Q}$	Heat flow ($J\ s^{-1}$)
U	Internal energy (J)
$\dot{E}$	Enthalpy flow ($J\ s^{-1}$)
Ex	Exergy (J)
V	Volume (m^3)
$\dot{V}$	Volume flow ($m^3\ s^{-1}$)
X	Position (m)
$\dot{X}$	Speed ($m\ s^{-1}$)
T	Temperature (K)
p	Pressure (Pa)
ω	Rotational speed (Hz)
τ	Torque (N m)
A	Surface area (m^2)
Re	Reynolds number
Pr	Prandtl number
F	Force (N)
K	Heat transfer coefficient ($W\ m^{-2}\ k^{-1}$)
D	Diameter (m)
R	Universal gas constant ($N\ m\ kg^{-1}\ K^{-1}$)
k	Heat capacity ratio
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume

Subscripts

s	suction
i	inlet
e	exit
E	Exhaust
u	upstream
d	downstream
r	ratio
R	Reservoir
p	piston
w	wall
v	valve
c	cylinder
Atm	Atmosphere

Comprehensive compressor models have been developed for different compressor types (Bradshaw et al., 2011; Chen et al., 2002a, 2002b; Kim and Groll, 2007). However, graphical representation of such models has been scarce so far.

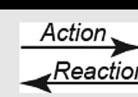
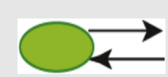
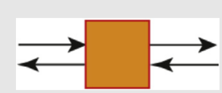
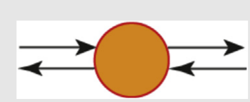
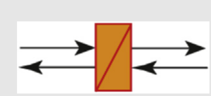
The graphical modeling based on EMR has advantages such as readability, modularity and functional characteristics. As regards the graphical modeling tools, their interest is double: firstly during the modeling phase itself and secondly as the easiest transfer of knowledge to the other users (Borutzky, 2009).

In some literature, graphical models of air compressor can be found (Engja, 1985; Karnopp and Rosenberg, 2000). They are based on the same equations and theoretical backgrounds than the previous ones but the graphical methodology highlights the understanding of the device behavior in a significant extent. To describe the modeling of thermodynamic systems, Thoma and Ould Bouamama (2000) uses Bond Graph approach. Using the same tool, Karnopp and Rosenberg (2000) proposes an overall picture of the considered system in a synthetic approach. Even if Bond Graph tool is able to describe complex systems, Energetic Macroscopic Representation (EMR) has its own strengths. In fact, beyond its modularity and readability, EMR reveals functional characteristics to provide a good model description in agreement with physical (e.g. integral) causality (Hissel et al., 2008). Both Bond Graphs and EMR are obviously able to describe multiphysical systems, but there are nevertheless different features between them. The former is based on energy and data flow and uses a uniform representation for all types of physical systems; while with the latter specific pictograms are used and associated to each power component increasing its readability. As a matter of fact, it shows the different physical domains crossed by the energy flows.

Therefore, a complex system of several energy sources and several energy conversion units can be accurately modeled and then described by the EMR tool with a clear readability.

Though EMR has been firstly developed to describe electromechanical system, Chrenko (2008) made it possible to extend it to new energy domains. Expanded to electrochemical, thermodynamical, thermal and fluidic domains, EMR has allowed describing many devices such as fuel cells systems, electromechanical systems, electrical or hybrid vehicle systems.

Table 1 – Energetic Macroscopic Representation blocs.

Pair of action and reaction	
Source of energy	
Energy conversion same domain	
Energy conversion different domains	
Energy accumulation	
Thermo-fluidic causalities (three and four variables both for gas and liquid)