INTERNATIONAL JOURNAL OF REFRIGERATION 69 (2016) 28–41

Available online at www.sciencedirect.com

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Transient cycle simulation of domestic appliances and experimental validation

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ARTICLE INFO

Article history:
Received 9 February 2016
Received in revised form 2 June 2016
Accepted 4 June 2016
Available online 10 June 2016

Keywords:
Transient
Simulation
Experiment
Cycle
Freezer
Heat exchanger

ABSTRACT

This work gives insight in the development and the application of a semi-implicit transient cycle simulation tool. The model consists of subcomponents that are independently validated and coupled in order to shape a fully functional cycle simulation. The methods used comprise empirical models, artificial neural networks or more complicated, transient 1d finite volume formulations for two-phase flow.

The validation of the cycle simulation is carried out using data from a specially equipped domestic freezer. The model is calibrated to one operating point and afterwards tested under varying ambient temperatures and thermostat settings. The agreement compared to measurements is 6.9% mean and 5.5% standard deviation of the total electric energy consumption. Furthermore, parameters like refrigerant distribution, pressure drop, temperature or mass flow rate can be monitored.

Simulation du cycle transitoire d'appareils électroménagers et validation expérimentale

Mots clés : Transitoire ; Simulation ; Expérience ; Cycle ; Congélateur ; Échangeur de chaleur

1. Introduction

"Energy efficiency" is an expression that has become part of everyday's vocabulary. No matter if domestic appliances, cars, buildings or lighting are regarded, this expression is not just a fashionable phenomenon of the 21st century, but a part of a global process as an answer to the increasing need for energy in more and more densely populated areas. With the help of directives and acts enforcing efficient use of energy in

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http://dx.doi.org/10.1016/j.ijrefrig.2016.06.007

Nomenclature

$a_1 \ldots a_5$	fit parameter
A	cross sectional area [m^2]
c_p	specific heat capacity [J kg^{-1} K^{-1}]
D	run time ratio
h	enthalpy [J kg^{-1}]
l	layer thickness [m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg s^{-1}]
p	pressure [Pa]
P	power [W]
$\dot{Q}$	heat flow rate [W]
Q_0	cooling capacity [W]
t	time [s]
T	temperature [K]
v	specific volume [m^3 kg^{-1}]
V	volume [m^3]
$\dot{V}$	volume flow rate [m^3 s^{-1}]

Subscripts

amb	ambient
comb	combined
comp	compressor
dis	discharge
el	electric
in	inlet
interp	interpolated
out	outlet
ref	reference
shell	compressor shell
sim	simulated
suc	suction
vap	vapour
V	volumetric

Greek symbols

α	heat transfer coefficient [W m^{-2} K^{-1}]
Δ	difference
η	efficiency
κ	heat capacity ratio
λ	heat conductivity [W m^{-1} K^{-1}]
ρ	density [kg m^{-3}]

different fields of industry and private life, manufacturers are forced to consider this topic in order to still be competitive in the future.

Also in the field of domestic refrigeration, which contributes to roughly 10 to 30% of a private household's electric energy consumption (IEA, 2009), the term "energy efficiency" has gained a foothold. The introduction of energy labels like the Directive 2010/30/EU stimulates the effort of developing highly sophisticated refrigeration applications. Therefore, the detailed understanding of the working principle of the refrigeration cycle is a necessity. Comprehensive component level knowledge is necessary, but not sufficient enough for the prognosis of the cycle behaviour, which can be highly transient. Due to the fact that the main components – compressor, expansion device, condenser and evaporator – are linked within a closed loop, a change in one of these parts influences all the others. At this point, computerized tools such as cycle simulations offer considerable advantages compared to experimentally induced investigations. A few reasons therefore are: The experimentally evaluated energy consumption of a domestic refrigeration application needs climatized rooms, several days of preparation, settling and measuring time. In a simulation, the ambient conditions can be held constant, components can be easily replaced and the speed of the algorithm can be tuned in order to exceed real-time. These advantages are the motivation for the following work where a transient cycle simulation tool is presented.

Research, supported by cycle simulation tools, started in parallel with the development of computers. Existing detailed summaries of cycle simulations in refrigeration can be found in Bendapudi and Braun (2002), Philipp (2002), Hermes and Melo (2008) or Ding (2007). The use of such tools is reported up to 40 years ago, where a crucial point was the treatment of the dynamics of heat exchangers. At the beginning, the two phase region was commonly treated with the lumped parameter approach, where the heat exchanger is reduced to a single thermodynamic state (0d). A little more evolved and widespread in this field is the moving boundary approach, where the domain is divided into two to three cells, which represent a volume of different refrigerant states (liquid, two-phase, vapour). The most evolved is the distributed parameter model, which equals a 1d representation of the heat exchanger domain. The modelling of the compressor also differs in literature. Simple empirical models are common, whereas time-resolved movements of the piston and the compressor valves are rarely seen. Due to the difference in time scales – the experimental energy consumption of a refrigeration device is defined as an average over 24 hours (up to 72 hours, according to present standard IEC 62552:2007), whereas the compressor valves open according to the rotational speed of the motor commonly 50 times per second – the compressor model is usually highly simplified. The simplification comprises steady-state assumptions of the mass flow rate. Transient effects in the compressor model are introduced by thermal masses or the oil/refrigerant interaction. The expansion device is in most cases a capillary tube which is available to the cycle simulation in the form of an empirical equation or a map. The cabinet or compartment is usually lumped to several thermal masses or it consists in the simplest case of a temperature dependent steady-state heat load.

Two cycle simulations shall be mentioned exemplarily, namely Philipp (2002) and Hermes and Melo (2008). Both works provide a comprehensive view on the numerics of their approaches, additionally, their schemes are also used for modelling domestic refrigerators.

Philipp (2002) provides insight in his cycle model for domestic refrigerators by presenting all sub-models as well as the overall system. He uses the moving boundary approach in combination with either homogeneous assumption or a slip model for the heat exchangers. The compressor model consists of semi-empirical formulations for the mass flow rate and the electric power. The shell side heat transfer is calculated by taking convection and radiation into account. Detailed investigations concerning the oil/refrigerant interaction have been carried