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A test procedure for energetic and performance analysis of cold appliances for the food industry

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Abstract. In this article we present a novel approach for the characterization of cold appliances and in particular of refrigerators based on the standard vapour compression cycle with a reciprocating on/off compressor. The test procedure is based on a virtual instrument that perform both the stimulus and the data acquisition on the device under test. Acquired data is elaborated to fit a semi-empirical model based on the energetic balances between thermal and electrical sub systems and the heat exchanged with the environment. This approach results in a simple method to calculate useful parameters of the refrigerator, such as energetic performance, cooling effect and limit values of thermal loads. The test procedure requires only a few temperatures and the electric power consumption to be monitored, resulting in a low impact on the refrigerator. Preliminary tests showed a good estimation of parameters and prediction of energy consumption and heat extraction capacity of the refrigerator under test.

1. Introduction

Domestic and professional refrigerators are a large energy demanding appliances in both emerging and developing countries. In particular household refrigerators cover the 15% of the domestic power needs[1,2]. Their capillary spread over the entire food chain, combined with the 24 hours a day use, justify this energetic demand and make important even the smallest energy efficiency improvement.

Performance enhancement of refrigerators is being addressed by different points of view[3]. Thermal insulators, high heat capacity materials, novel refrigerant fluids, stirling[4] and linear compressors, thermo-acoustic[3] and magneto-thermal[5] effect are all subjects of great interest as promising means to improve the efficiency of refrigerators. From the other point it looks clear that the energetic efficiency of a refrigerator can also be increased by users with their own actions. Several studies have underlined that a 10%–20% of energy consumption in the domestic sector could be saved by modifying the sole behaviour of the occupants[6,7]. A real–time feedback on refrigerator energetic needs have been identified as an essential information to help individuals improve energy–use behaviour[8,9].

Useful information on the state of the refrigerator such as electrical power consumption, performance or heat extracted from the cabinet are difficult to measure directly without a complex acquisition system. An estimation of these values can be determined with the support of a behavioural model of the refrigerator tuned on its load characteristics. The components to be taken into account to characterise refrigerators and in general cold appliances are heat pump (generally compressor, evaporator and isenthalpic valve), cabinet or room to be cooled and external environment (temperature and humidity). To characterise the entire refrigerator the layout of the components in the cabinet and their interconnection must be taken into account as well because the overall performance is strongly related to the practical assembly of the system. This implies that the real behaviour can’t be defined by the sole combination of the characteristics of its components but require an overall performance characterisation. Moreover cold appliances are in general non-linear systems, thus their characterisation requires multiple points of load and environmental conditions to be acquired.

Standard procedures to characterize a refrigeration compressor are mainly based on the measurement of its values of temperature, power consumption, pressures and extracted heat at different points of its load curve. The approach here proposed draws from this method, in which the refrigerator is characterized as a whole over its entire range of loads and ambient temperatures. This method is associated to a mathematical model which is based on the balances between the different energy components that describe the refrigerator. In the stationary state heat extracted by the thermodynamic cycle compensates thermal load of food and insulation losses. The load curves for different ambient temperatures are used to tune the model which is then able to emulate the behaviour of the refrigerator and provide useful information such as cell thermal conductivity, amount of net heat extracted from the cell and electrical power consumption. The simplified thermodynamic equations are derived from the steady state semi empirical approach proposed by Gonçalves et al.[10] and Hermes et al.[11].

This article presents this approach to the characterisation of a professional refrigerator and provide a first experimental validation of the underlying model. The tests were performed in a climatic room and with a controlled heat source positioned in refrigerator cell to achieve the entire range of loads and temperatures defined by the main test standards[12,13] while maintaining the stationary condition.

2. Experimental setup

The semi-empirical model emulates the steady state behaviour of a vapour compression cycle refrigerator, in which the reciprocating compressor is controlled by an on/off type thermostat. The mathematical approach is similar to those proposed by Gonçalves et al. and Hermes et al., in which the refrigerator is divided into sub-systems (Figure 1), namely compressor, evaporator, heat exchanger, capillary valve, condenser and refrigerator cell.

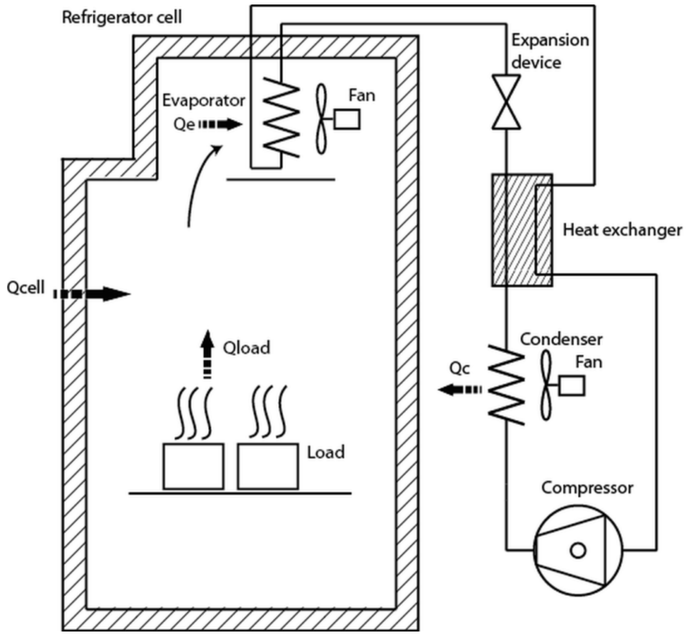

Figure 1. Simplified diagram of a vapour compression cycle refrigerator.

In this work the thermal load absorbed by the evaporator is divided in three contributions:

- Heat introduced in the cell by insulation losses
- Heat produced by electric equipment located in the cold compartment (evaporator fan, defrost heater, door heater and cell lamp)
- Heat released by the food present in the cold compartment, including pans, grids and moist air introduced when the door is opened.

Each sub-model is described by its simplified thermodynamic behaviour; refrigerant enthalpy and mass flow rate are the state functions that connect these subsystems.

The experiments were designed to achieve two different tasks: sub models verification and model fitting. First a large amount of data was collected to verify that each part of the overall model was coherent with the real behaviour of refrigerator's related element. The second task was to provide the model with sufficient data to allow parameter fitting procedure. A second set of data was used to evaluate model prediction capabilities.

All of the experiments have been performed under stationary conditions of ambient temperature, while in the climatic chamber humidity was kept at values below 20%. In order to emulate food contribution to the thermal load, a controllable constant heat source was placed in the refrigerator cell. The methodology has been tested with a standard 500l, single door professional refrigerator with a R134a vapour compression cycle, a GL90TB reciprocating compressor and fin tube evaporator and condenser. Ambient temperature and humidity were imposed by the use of a climatic room with a ±2°C temperature error. Temperatures were acquired using a set of T-type thermocouples connected to a NI thermocouple data acquisition system (±0,1°C error). The pressure transducer mounted on the suction side of the compressor had a 0,1Bar resolution. Power measurements were performed with a WT500 and a Microvip3 electrical power meters (±0,1W and ±0,5W error respectively).

Thermal load supplied to the refrigerator's cell through electric resistors is equivalent to extracting heat from a constant heat source. In this way electrical/thermal dummy loads are intended as a useful way to emulate any kind of food and its load profile (humid air could be included as well, with proper assumptions on the heat exchange performance of the evaporator). The net thermal load was introduced in the refrigerator cell by turning On and Off the electrical power supplied to a rack of 4 power resistors. Resistor values were calculated to dissipate a nominal power of 25W, 50W, 100W and 200W. In such way it was possible to supply 16 values of power between 0W and 375W, with a step resolution of 25W.

Each experiment comprised of a preliminary phase to allow transients due to ambient temperature or power variations to be settled. The acquisition phase was set to 2 hours with a sample rate of $1Sas^{-1}$. Two sets of experiments were performed. The first one comprised 270 experiments of 2 hours each. This data was then used to fit model's parameters. A second set of 20 experiments was then performed and used as validation data. These experiments covered the range of thermal loads between 0W and 250W and ambient temperatures between 14°C and 43°C.

A system of virtual instruments, developed in Labview environment, performed tasks of data acquisition and control of thermal load supplied by the heaters. A first VI generated the stimulus to control the climatic room and the heat source inside the refrigerator's cell. A second VI collected the data from the various measurement units. After each test, acquired data was elaborated with another VI to calculate the enthalpy of the refrigerant in points of interest in the thermodynamic diagram. Values were calculated for the compressor On state only; in the Off phase it was assumed there was no refrigerating effect, as evaporator's fan was stopped, thus reducing significantly the air flow through the evaporator.

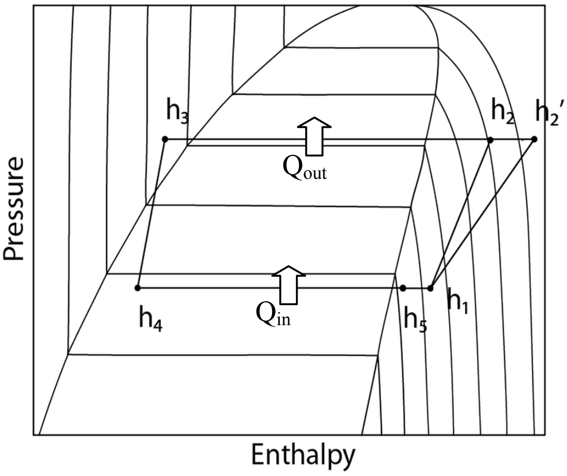

Figure 2. Simplified P-h diagram of the refrigeration cycle.

Look-up tables derived from the NIST database were used to relate R134a refrigerant enthalpy and entropy to its temperature and pressure in different points of the P-h vapour compression cycle diagram (Figure 2). Activation period, duty cycle, on state, average electrical power and average value of temperatures were calculated. Average values of thermodynamic properties such as isentropic compression enthalpy and extracted and rejected heat were provided as well. Concluding, each set of data, related to a 2hrs test, was then reduced by averaging each parameter. Values were split in two groups, associated with the state of the compressor. Thus thermodynamic properties, temperatures and electrical powers were averaged for both the ON and OFF states of the compressor.

3. Results

A refrigerator that works on a stationary condition can be defined by mainly four parameters, these are ambient temperature, electrical power consumption, heat load in the refrigerated cabinet and compressor's duty cycle.

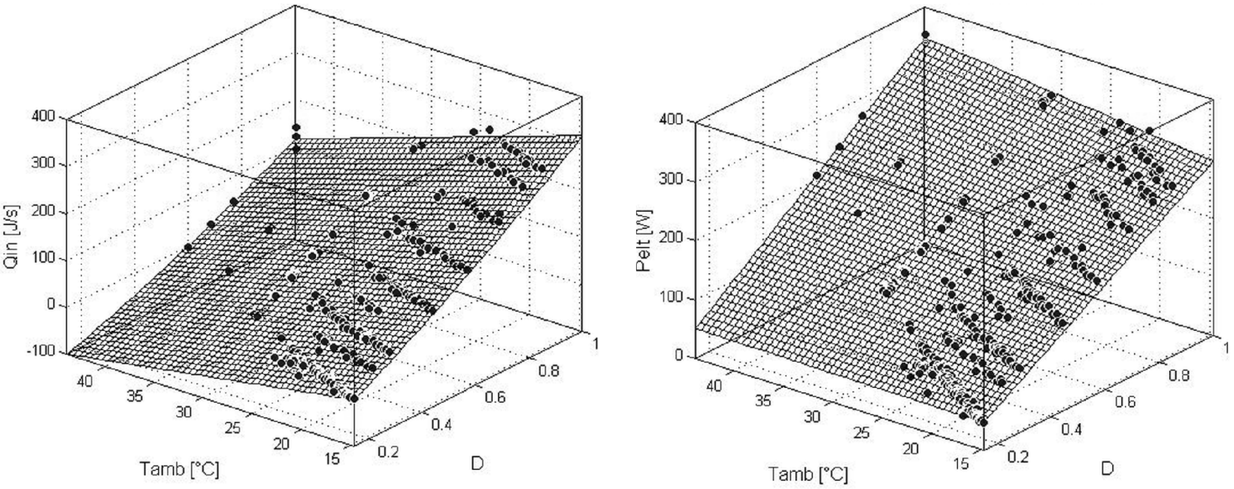

Figure 3. Net heat load (left) and electrical power consumption (right) as a function of ambient temperature and duty cycle.

In Figure 3 are reported experimental data (dots) and model response (surfaces) of heat load and electrical power consumption as functions of ambient temperature and duty cycle.

A preliminary validation of the model is reported in Figure 4. The measured and predicted heat load in the refrigerated cell and the electrical power consumption are compared. These show good agreement between the model and the device under test. An important coefficient derived from the model is the thermal insulation of the refrigerator cell. For the DUT its estimated value was 2.4 W/°K, that is in good agreement with the 2.5 W/°K stated by the constructor of the refrigerator.

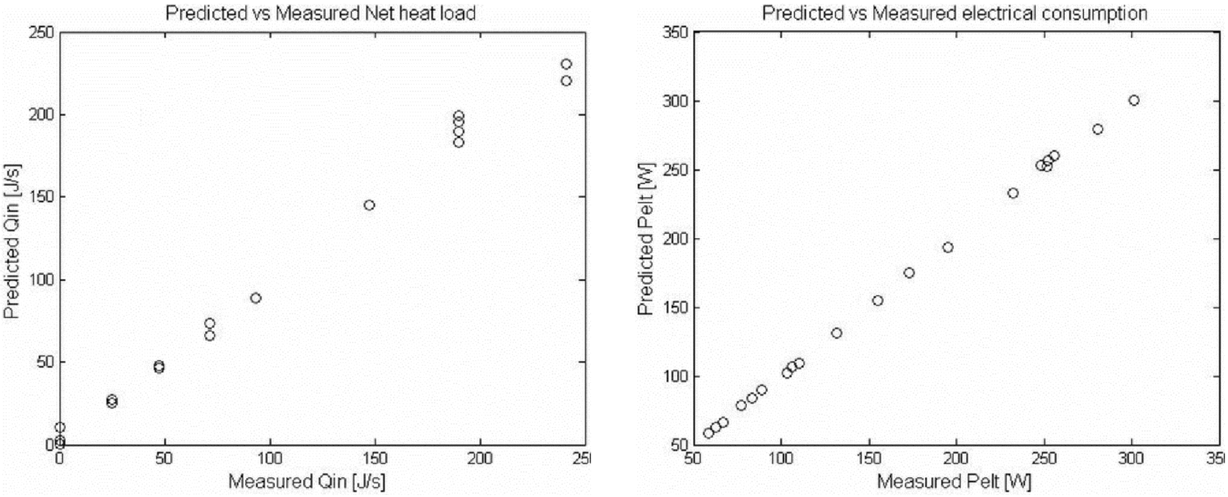

Figure 4. Comparison between predicted and measured heat load (left) and electrical power consumption (right).

4. Conclusions

A novel method for the characterisation of professional cold appliances has been proposed. A first evaluation has underlined its capabilities to assess the performance and maximum load of a refrigerator, with minimal computational requirements and with minimal effort on the device under test. Although a large amount of data has been collected, the method requires only three temperature sensors and a power meter to monitor electrical consumption.

The same method can be used to generate a model with good capabilities in the prediction of the power consumption of the refrigerator and its thermal load response over the entire range of ambient temperatures indicated in the international standards for professional refrigeration. This approach could represent a simple solution for the characterisation of the refrigerator in function of other parameters, such as door opening events, defrost cycle etc. and for the estimation of the thermal load associated to different foods. It is also suitable to be embedded in the refrigerator in order to provide the user with real time estimation of power consumption and cooling capability.

Ageing of components of the refrigerator is a topic that needs to be inspected as well to assess whether a duty cycle-based characterisation of the machine can be used over the entire life-time of the appliance.

Although this method based on steady state energetic balance has been proposed for refrigerators it can be adapted to other kind of cold appliances such as blast chillers and in general HVAC. The advantages could be the low impact on DUTs and the capability to evaluate their entire load curve in a limited set of experiments.

References

[1] IEA 2008 Worldwide trends in energy use and efficiency: key insights from IEA indicator analysis, IEA/OECD, Paris, www.iea.org/papers/2008/indicators_2008.pdf
[2] Bertoldi P, Atanasiu B 2009 Electricity and Consumption Efficiency Trends in European Union

- Status Report. EU Commission Joint Research Centre ISBN 978-92-79-13614-6, EUR 24005 EN
[3] Tassou S A, Lewis J S, Ge Y T, Hadawey A, Chaer I 2010 A review of emerging technologies for food refrigeration applications *Applied Thermal Engineering* **30** 263-276
[4] Thombare D G, Verma S K 2008 Technological development in the Stirling cycle engines *Renewable and Sustainable Energy Reviews* **12** 1-38
[5] Yu B, Liu M, Egolf P W, Kitanovski A 2010 A review of magnetic refrigerator and heat pump prototypes built before the year 2010 *International Journal of Refrigeration* **33** 1029-1060
[6] Owens J, Wilhite H 1988 Household energy behavior in Nordic countries-an unrealized energy saving potential *Energy* **13** 853-859
[7] Nielsen L, 1993 How to get the birds in the bush into your hand. Results from a Danish research project on electricity savings *Energy Policy* **21** 1133-1144
[8] Mansouri I, Newborough M, Probert D 1996 Energy consumption in UK households: Impact of domestic electrical appliances *Applied Energy* **54** 211-285
[9] Wood G, Newborough M 2003 Dynamic energy-consumption indicators for domestic appliances: Environment, behaviour and design *Energy and Buildings* **35** 821-841
[10] Gonçalves J M, Melo C, Hermes C J L 2009 A semi-empirical model for steady-state simulation of household refrigerators *Applied Thermal Engineering* **29** 1622-1630
[11] Hermes C J L, Melo C, Knabben F T, Gonçalves J M 2009 Prediction of the energy consumption of household refrigerators and freezers via steady-state simulation *Applied Energy* **86** 1311-1319
[12] Bansal P K 2003 Developing new test procedures for domestic refrigerators: Harmonisation issues and future R&D needs - A review *International Journal of Refrigeration* **26** 735-748
[13] Mahlia TM I, Saidur R 2010 A review on test procedure, energy efficiency standards and energy labels for room air conditioners and refrigerator-freezers *Renewable and Sustainable Energy Reviews* **14** 1888-1900
[14] Ding G L 2007 Recent developments in simulation techniques for vapour-compression refrigeration systems *International Journal of Refrigeration* **30** 1119-1133