UPC **CTTC**

Development of experimental and numerical infrastructures for the study of compact heat exchangers and liquid overfeed refrigeration systems

Centre Tecnològic de Transferència de Calor
Departament de Màquines i Motors Tèrmics
Universitat Politècnica de Catalunya

Stoyan Viktorov Danov
Doctoral Thesis

Stoyan Viktorov Danov

DOCTORAL THESIS

UPC – November 2005

Development of experimental and numerical infrastructures for the study of compact heat exchangers and liquid overfeed refrigeration systems

Stoyan Viktorov Danov

TESI DOCTORAL

presentada al

Departament de Màquines i Motors Tèrmics
E.T.S.E.I.T.
Universitat Politècnica de Catalunya

per a l'obtenció del grau de

Doctor Enginyer Industrial

Terrassa, November 2005

Development of experimental and numerical infrastructures for the study of compact heat exchangers and liquid overfeed refrigeration systems

Stoyan Viktorov Danov

Director de la tesi

Dr. Carlos David Pérez-Segarra
Dr. Assensi Oliva Llena

Tribunal Qualificador

Dr. José Maria Sala Lizarraga
Universidad del País Vasco
Dr. Joaquim Rigola Serrano
Universitat Politècnica de Catalunya
Dr. Agustín Macias Machín
Universidad de Las Palmas de Gran Canaria
Dr. Enrique Velo García
Universitat Politècnica de Catalunya
Dr. José Manuel Cejudo López
Universidad de Málaga

Acknowledgements

To my wife Gabi for being with me, and for her patience, understanding, and moral support through these years.

To Assensi Oliva who made possible my work in the CTTC and supported me completely in the work, the administrative troubles, and personally.

To Carlos David Pérez-Segarra for his guidance, assistance and help in the development of the thesis, and also for his suggestions and critics to it.

To Carles Oliet for helping me with the use of the numerous informatics tools employed in this work, and for his ideas and collaboration.

To Gustavo Raush for his indispensable help in the experimentation, providing me his knowledge in data acquisition, and for the fruitful discussions with him.

To Manuel Ordoño for his help in the construction of the experimental facilities, and his suggestions to make things better and easier.

To Octavio García for introducing me to the two-phase flow simulation, for his contribution to the experimental infrastructure development, and for his friendship.

To Ricard Consul for his help to initiate me in the computational fluid dynamics and the SIMPLE programming.

To Ramiro Alba and Daniel Fernández for their support in informatics allways when I needed it.

To Guillem Colomer for his discreet help for fixing the LATEX handicaps in writing the thesis.

To Marcos Quispe, Raul Massipe, Concepció Lifante, Ivette Rodríguez, Debora Faggembauu, Joaquim Rigola, Jesus Castro, Jordi Cadafalch, Manel Soria, Kilian Claramunt for their comradeship and friendship.

To the AECI for granting me the doctorate fellowship.

To my wife Gabi
and my son Georg

Abstract

Experimental infrastructures intended for validation of compact heat exchanger models, and models of liquid overfeed refrigeration systems and their components, have been developed and constructed. The aim has been the obtaining of reliable experimental data from tests at exactly defined geometrical and boundary conditions, permitting the unequivocal comparisons with numerical simulation results.

The mathematical models are presented and detailed description of the air-handling, the liquid refrigerant, and phase-changing refrigerant circuits integrating the experimental infrastructure is given. These three circuits are encharged to provide stable controlled conditions for the tested prototypes and the liquid overfeed system in the desired range of temperatures, fluid flows, and capacities. The design permits the accommodation of heat exchanger prototypes with different geometry and sizes. Detailed overview of the measuring instruments is presented, with their accuracies and mounting, and the components and parameters of the data acquisition system are described.

Special attention has been paid to the calibration of the measuring instruments as an essential part of the test preparation. The process of estimation of the systematic uncertainties in the calibrated sensors' measurements is described. The formulation and the methodology adopted for the uncertainty analysis of the experimental results is exposed in detail.

The experimental data processing and analysis has been performed automatically with a specially developed program encharged with the calculation of the experimental results from the measured variables, the detailed uncertainty analysis, and the numerical to experimental results comparisons.

Experimental results obtained with the developed infrastructure are presented. Detailed studies of compact heat exchangers under cooling conditions, using liquid and phase-changing refrigerants, are performed and presented. Results from the experimental studies of the liquid overfeed refrigeration system are also presented. The results have been checked and verified through energy balance checks for all the components where measurements of the same physical magnitude can be contrasted with independent measurements. In order to give more general use of the obtained experimental data, the raw measured variables during the tests are also presented.

An experimental validation methodology for the compact heat exchanger model has been proposed, based on systematic comparisons between numerical and experimental results. The comparisons have been analysed in statistical terms in order to quantify the observed differences and to give global evaluation of the numerical model performance in the tested conditions. The methodology proposed for validation of the heat exchanger model can be used as a basis for validation methodology for numerical models in general.

Contents

6 Conclusions and future actions 151

Stoyan Viktorov Danov, *Development of experimental and numerical infrastructures for the study of compact heat exchangers and liquid overfeed refrigeration systems,* Doctoral Thesis, Universitat Politècnica de Catalunya, November 2005.

Chapter 1

Introduction

1.1 Preface

Since its beginning about 150 years ago, the refrigeration and air-conditioning have produced an enormous impact over the human life, finding applications actually in all kind of industry, office and home, becoming an industry itself. In the early years of the refrigeration industry the three basic refrigeration techniques were vapour absorption, cold air systems, and vapour-compression systems, which eventually became the standard for the refrigeration systems.

As a concept refrigeration has changed little since the early 1900's, relying on fluid refrigeration in a closed cycle evaporation, compression and condensation. Most of the work this century has been spent on refining the details of the system, seeking the most efficient refrigerant, developing better compressors, and working out the most efficient arrangement of components and pressures for the desired operating temperatures.

Heat exchangers are key elements in refrigeration and air-conditioning systems. Numerous designs and applications for evaporators and condensers have been developed throughout the years. The applications of evaporators in refrigeration and air-conditioning installations can vary substantially depending on the pursued objectives, but they can be divided depending the methods of refrigerant feed into: direct expansion evaporators, flooded evaporators and liquid overfeed evaporators. In direct expansion evaporators the refrigerant is dosed with the expansion valve in function of the super-heat of the vapour of the completely evaporated refrigerant. They are widely used with freons at moderate refrigerating temperatures. At lower evaporating temperatures, the inherent super-heating of the refrigerant near the end of the evaporator imposes progressively severe penalty in capacity and operating efficiency. This type of application is not widely used with ammonia because the low flow-rates of ammonia for a given refrigerating capacity are sometimes difficult for the expansion valve to control. The flooded evaporator relies on natural convection to circulate more refrigerant through the evaporator than what evaporates. In the liquid overfeed evaporators, a liquid refrigerant above the evaporating rate is supplied with the means of a pump or gas pressure, so that the refrigerant at the outlet is a liquid-vapour mixture. The vapour formed in the evaporator is separated in a vessel and flows to the suction of the compressor. The surface of the flooded and liquid overfeed evaporators is more efficiently used because of the good refrigerant distribution and the completely wetted internal tube surfaces, but for small systems the initial cost is higher.

Despite of the inherent advantages, refrigeration had its problems. The refrigerants used in the early vapour compression machines, like sulfur dioxide, methyl chloride, ammonia and some hydrocarbons were all toxic or flammable, which limited their use mainly to industrial applications. In 1928 a new class of synthetic refrigerants called CFCs (chlorofluorocarbons, commonly known by the trade name “Freon”) have been discovered, solving the dangerous problem of toxic, flammable refrigerants. The introduction of the CFCs and the later development of new synthetic compounds as HFCs (hydrofluorocarbons) and HCFCs (hydrochlorofluorocarbons) gave a strong push of the refrigeration industry into the household market and the comfort air-conditioning. In 1974 Sherwood Rowland and Mario Molina in their article [1] predicted that chlorofluorocarbon gases would reach the high stratosphere and damage the protective mantle of the oxygen allotrope, ozone. In 1985 the “ozone hole” over the Antarctic had been discovered.

The concern about the ozone layer depletion and the global warming, related with the emission of artificial chemical compounds has led in the recent decades to international agreements aiming the ban of some widely used refrigerants. In 1987 the Montreal Protocol [2] appears with the objective to protect the stratospheric ozone layer and condemns the CFCs and the HCFCs to phase out as compounds depleting the ozone layer. Then the group of useful refrigerants was reduced to hydrofluorocarbons (HFCs) and natural refrigerants. In 1997 the Kyoto Protocol [3] determinates “to achieve stabilization of atmospheric concentrations of greenhouse gases at levels that would prevent dangerous anthropogenic (human-induced) interference with the climate system...” and encourages to promote policies and measures to sustainable development. The global warming potential (GWP) of HFC gases is high, which obliges that these kind of gases to be regulated.

The increasing of the energy consume in the developed societies, as a consequence of the continuous industry growing, is by a significant part due to the energy consume of the refrigeration and air-conditioning equipment. The sustainable development, permitting the satisfying of the present necessities without putting at risk the future generations, is challenging the refrigeration and air-conditioning industries in increasing the energy efficiency and to develop alternatives for the “classical” refrigerants, used for years.

The advances in computational sciences permitted the development and implementation of mathematical models for simulation of refrigeration systems and equipment. The complex phenomena involved in these equipment can be resolved with less restrictions using numerical methods, than with the traditionally used analytical methods, offering possibilities for considerable design and performance improvements of either components and systems.

The activities of the CTTC in the refrigeration field started at the late 80s with numerical modeling of components, such as condensers, evaporators, expansion devices and compressors. This work gave place to various publications through the next years, [4], [5], [6], to mention a few. The close collaboration with the company Unidad Hermetica (nowadays ACC Spain S.A.) permitted the development of experimental set-up for testing of compressors and double-tube evaporators and condensers. A fin-and-tube heat exchanger model, consolidated under the name CHESS (Compact Heat Exchanger Simulation Softwear), was developed and improved, [7], [8], [9], [10].

But in order mathematical models for simulation to be introduced as essential and reliable tools for optimization, design, construction improvement and decision making in industrial applications, they should be first thoroughly validated experimentally.

The experimental validation is intended to demonstrate the adequateness of a mathematical model in representing the real phenomena and establish a level of credibility in the produced results. In his book [11] Roache provides a more expanded definition of the validation, citing Mehta [12]: "Validation is defined as the process of assessing the credibility of the simulation model, within its domain of applicability, by determining whether the right simulation model is developed and by estimating the degree to which this model is an accurate representation of reality from perspective of its intended uses."

Experimental data accuracy is essential for the performance of correct validation process. Many scientific works emphasize on this important point. Marvin in [13] notes "Accuracy assessments for experimental data are essential; otherwise there is no quantitative means for determining the validated range of the code. ... Uncertainty analysis is a well established method for determining experimental data accuracy, and it should be a prerequisite for all validation databases."

Every experiment has some uncertainty associated with the results, and certainly there is no sense to look for comparisons finer than this experimental uncertainty. As Coleman [14] states, "the (experimental) uncertainties should set the scale at which comparisons should be made or attempted. This holds for data-data, model-data, and model-model comparisons."

The work in this thesis has been motivated from the need for experimental validation of the compact heat exchanger simulation model CHESS, mentioned earlier, and the liquid overfeed refrigeration system model [15]. The objective has been the development of infrastructure permitting the generation of accurate experimental data from tests with compact heat exchangers and liquid overfeed systems under controlled conditions. The experimental data should be used for validation of the mathematical models, and adequate validation procedures should be developed for assessment of the numerical results.

1.2 Literature review

The compact fin-and-tube heat exchangers are commonly used in the field of thermal engineering. Some of the most widely spread applications are evaporators and condensers in refrigeration machines, air heating, cooling, and dehumidifying in air-conditioning systems, automotive radiators, etc. The phenomena in these equipment are very complex due to the three dimensional geometry, complex flow patterns, and the fin performance changes, influenced by the combined heat and mass transfer associated with cooling and dehumidifying of air. This has given place to numerous analytical and numerical approaches to their resolution, and extensive experimental studies. Analytical solutions are limited and suppose the assuming of stringent simplifications, as steady state regime, uniform heat transfer coefficients, constant thermo-physical properties. Numerical methods allow solutions of the heat exchangers to be found with less restrictions.

The complex system behaviour and interactions between the components of refrigeration systems is difficult to be studied analytically. This has given place to mathematical modeling and experimental studies, centred mainly in single stage direct expansion systems due to their extended use. Liquid overfeed refrigeration systems have received less attention in the open literature in recent years, although being of great importance for industrial refrigeration.

A review of mathematical models of compact heat exchangers and refrigeration systems, and experimental studies with them, published in the scientific literature is presented subsequently.

1.2.1 Compact heat exchangers

In the late years has grown the interest in studying heat exchanger performance because of the increased searching for higher efficiency and lower cost through the use of improved geometries, and the use of different working fluids. Different numerical models have been published in the literature, with the attention mainly focused on the simulation of condensers and evaporators, being the case of single-phase heaters/coolers a particular situation.

Jia et al. [16] presented a detailed model to predict the transient behaviour of fin-and-tube evaporators, with a tube-element discretization basis. The refrigerant distribution and the heat transfer coefficients on the air side were supposed to be uniform, the air was taken as incompressible and the heat conduction along the tubes as negligible.

Bensafi et al. [17] presented an interesting steady-state model, with a tube-element discretization, with high circuitry possibilities. The heat conduction along the tubes was supposed negligible. The refrigerant heat transfer coefficient is calculated at each step and used as a local value. The air heat transfer coefficient is supposed constant throughout a row of tubes, or the whole circuit if desired. F-factor correction has been applied to the calculated heat transfer between both fluids to account for the effect of cross-flow.

Chow [18] presented a complete and interesting review of the computer simulation evolution over air coolers. It was also presented a transient detailed model based on a tube-by-tube basis.

Wang and Touber [19] presented a tube-fin element based detailed non-steady state model, which takes into account the heat conduction between the tube-fin element nodes. The air was supposed without mass or energy accumulations.

Oliet et al. [9], [10], presented the detailed compact heat exchanger model CHESS, analysing the heat exchanger on the basis of discretization into fin-and-tube elements over which the governing equations are resolved. The convection refrigerant-side and the convection and mass transfer air-side are treated locally in an innovative way, using only basic empirical information about the local heat transfer coefficients and friction factors. The model uses variable thermo-physical properties, and considers the multidimensional heat conduction in tubes and fins.

Compact heat exchangers have been studied experimentally in numerous set-ups. The basic experimental test requirements for forced-circulation air-cooling and air-heating coils, the rating requirements, and the minimum data requirements for published ratings are established by the ARI Standard 410-2001 [20]. The basic methods for laboratory testing are proportioned in the ANSI/ASHRAE Standard 33-2000 [21]. Most of the presented in the scientific literature experimental facilities for testing of compact heat exchangers are in compliance with the above cited standards, or their previous editions, guided from the established principles, but using variety of test facility configurations and instrumentation. Basically two approaches for organizing of the air-flow through the tested heat exchanger are used: a wind tunnel, used in the experimental facilities [22], [23], and a climatic chamber as described in [24], [25], [26]. Both arrangements are used for creating of controlled temperature and humidity of the air at the inlet of the tested prototype. For the measurement of the air temperature thermo-couples distributed in the air cross-section [27] or thermopile grids [23] are used, or RTD measurements are implemented using sampling devices [26]. For the measurement of the air relative humidity the employed methods are dry and wet bulb temperature measurement using sampling devices [24], [26], chilled mirror hygrometer [22], and capacitance type relative humidity sensors [28]. The air-flow measurement in most of the experimental facilities is based on nozzle pressure difference measurement according to ASHRAE Standard 41.2-1987 [29].

1.2.2 Refrigeration systems

The development of mathematical models for the refrigeration system components has permitted their integration in system models. Different works have been presented in the literature, focusing their attention on modeling vapour-compression systems, their components, the overall refrigeration cycle, and the comparison of the numerical with experimental results.

Chi and Didion [30] modelized the transient performance of single stage heat pump. This model is based on zonal balances inside the condenser, evaporator and accumulator distinguishing liquid, vapour, two-phase flow, walls and external air. Parametric models based on empirical non-dimensional correlations have been carried out for the compressor and the thermostatic expansion valve. The states of the different components are described by a set of first-order differential equations and the numerical solution is obtained by the first order Euler method. Furthermore, this model considers the dynamic responses of electric motors, compressor, shaft, electric fans, heat exchangers, accumulators and thermostatic expansion valves.

Murphy and Goldsmith [31], [32] modelized the start-up and shut-down transient performance of a residential air-conditioner. All the elements are simulated using parametric models based on empirical non-dimensional correlations, except the capillary tube. The compressor is modelled by its steady-state equations. The capillary tube model is based on zonal balances distinguishing sub-cooled liquid and two-phase flow, integrating numerically the different terms and using average friction factors.

Rajendran and Pate [33] modelized the transient performance of a vapour-compression refrigeration system. This model is similar than Chi and Didion model. It is based on zonal balances inside the condenser, the evaporator and accumulator and parametric models based on non-dimensional correlations for the compressor and the thermostatic expansion valve. This model considers the transient pressure term for the refrigerant inside each component. The overall refrigeration system is a set of differential and ordinary algebraic equations. These equations are solved numerically using an explicit finite-difference method. There are no experimental comparative results.

MacArthur [34] modelized a transient vapour-compression heat pump system. The two heat exchangers are solved using finite difference method and considering a one-dimensional formulation of the governing equations, although in the energy equation the transient pressure term is not considered. The compressor is solved distinguishing different processes: the heat transfer in the suction and discharge ducts, the pressure drop in the suction valve, in the compressor chamber and in the discharge valve. The mass flow rate in the compressor and the thermostatic expansion valve are simulated using parametric models based on non-dimensional correlations. There is no comparison with experimental data.

Jung and Radermacher [35] modelized a single evaporator domestic refrigerator in steady state. The condenser and the evaporator models are based on zonal balances.

The compressor is considered a non-ideal isentropic compressor. The steady state thermal system simulation is solved using two techniques: the successive substitution method and the simultaneous solution Newton-Raphson method.

Yuan and O'Neal [36] modelized a freezer in transient simulation and solved all the elements, except the compressor, in one-dimensional analysis the governing equations of every control volume using an implicit finite difference method. The pressure drop inside the heat exchangers is ignored. The compressor is modelled as a whole, the compression process is considered polytropic, and the suction and discharge valves are considered adiabatic and isoenthalpic. The capillary tube is assumed to be one-dimensional and isoenthalpic. The outlet velocity of the condenser is assumed negligible. With these assumption the relation among the elements is coupled.

Escanes et al. [37] and Rigola et al. [38], [39] developed a numerical simulation of the thermal and fluid dynamic behaviour of a single stage vapour compression refrigerating system that was improved and adapted to be used under carbon dioxide fluid refrigerant properties. The modelization consists of a main program that sequentially calls different subroutines until the convergence is reached. The unit studied consists of a double-pipe condenser or gas cooler and evaporator, a capillary tube or expansion device, a hermetic reciprocating compressor, and different connecting tubes. Figure 1 presents the refrigerating unit scheme. The heat exchangers and the capillary tube are solved on the basis of a control volume formulation of the governing equations (continuity, momentum and energy), considering transient and one-dimensional flow. The creation of entropy is considered in the capillary tube in order to detect the limitation of the physical process produced under critical flow conditions. The compressor has been modelized by means of global balances between its inlet and outlet cross-section. This compressor model also needs some additional information based on the following parameters: the volumetric efficiency, the isentropic efficiency and the heat transfer losses through the shell efficiency. This information has been obtained using an advanced numerical simulation model of hermetic reciprocating compressors, numerically verified and experimentally validated, considering different pressure ratios and boundary conditions.

More recently, Khan and Zubair [40] evaluate the performance of a reciprocating refrigeration system, on the basis of different parametric studies, considering a lineal experimental evolution of and as function of evaporator and condenser temperatures. Several results are shown considering different working conditions, a variable-speed system, and sub-cooling and super-heating effects.

Koury et al. [41] present a numerical simulation model considering a variable speed refrigeration system. The compressor and expansion device are considered under steady state experimental data due to their very small thermal inertia, while heat exchangers are evaluated considering the two and three zone models for evaporators and condensers respectively. The numerical resolution is based on an iterative process, where some specific variables are determined from the Newton-Raphson method.

Most of the numerical models and experimental works for the study of the vapour-compression refrigeration systems are for single stage, direct expansion systems. Liquid overfeed refrigeration systems have received less attention in the recent years, as can be seen revising the open literature. Here can be mentioned the experimental work of Giuliani et al. [42] where the performance of a standard refrigeration system is compared with that of a liquid overfeed system, using pure refrigerant R134a and zeotropic mixture R32/134a.

1.3 Objectives, concept and methodology

The objective of this thesis has been the development of experimental infrastructures intended for validation of compact heat exchanger models, and models of liquid overfeed refrigeration systems, and their components. The aim has been the obtaining of reliable experimental data from tests at exactly defined geometrical and boundary conditions, permitting the unequivocal comparisons with numerical simulation results.

Although centred in the previously mentioned applications, the designed infrastructure should permit its expansion in the future to other applications in the refrigeration and air-conditioning fields, as direct expansion evaporator and system studies, refrigerated room studies, compressor studies, etc.

Together with the experimental infrastructure development, procedures for experimental tests and data processing and analysis should be elaborated. Assessment of the experimental data quality and accuracy should be done previously to its use for validation. An adequate validation methodology was needed for systematic comparison of the numerical and experimental results, and the confident quantitative evaluation of the models' performance. Considerable part of the work in the thesis has been dedicated to the development of principles and methodology, applied mainly to the validation of the compact heat exchanger model, that can also be used as guidelines for a validation methodology in general.

The conceptual development of the experimental structure started from the possibilities of the numerical models which validation was intended. The model of the fin-and-tube heat exchangers CHESS is able to simulate them using liquid and phase-changing refrigerant (evaporation, condensation), which led to the idea of developing two refrigerant circuits, one providing liquid refrigerant to the tested prototype, and other providing phase-changing refrigerant for tests of evaporators.

Firstly, considerations about the applications have been made. It was decided to prepare the facility for testing of air-coolers and evaporators in dry and wet conditions, because of the more complex phenomenology involved, consisting of sensible and latent heat transfer due to water vapour condensation over the fins of the heat exchanger. The ability of the model to simulate this phenomena should be tested. The temperature range was decided to be large, covering air conditioning and refrigeration applications, with refrigerant temperatures between approximately -20^oC and $+15^o$C, and air temperatures from -15^oC to $+50^o$C. Tests with temperatures below 0^oC would cause frost accumulation over the fins of the heat exchanger, complicating the experimental set-up, and have been postponed to a later phases of experimentation, when more experience would be acquired. The experimental studies should be centred over the positive temperature range, although the installations should be able to work either in the positive or negative temperature ranges.

For the liquid refrigerant circuit, a system with indirect cooling has been considered, permitting different refrigerants to be used in the tests. This system allows the control to be achieved by means of a specially designed chiller and a set-up using two independent refrigerant loops, developed to refine temperature control. The chiller is able to provide minimum 7 kW of cooling capacity with -20^oC refrigerant temperature, being its capacity much bigger in higher temperatures. It is also used to provide cooling to other experimental facilities, and also for air-conditioning of the adjacent laboratory rooms when unoccupied for experiments.

The system considered for the experimental phase-changing refrigerant circuit has been with mechanical liquid overfeed of the evaporator. This system combines features permitting experimental component testing, as evaporator, condenser, compressor, expansion device, etc., and also refrigeration cycle tests, giving wide spectrum of possibilities for experimental validation of the evaporator and the liquid overfeed refrigeration system models. The system permits large range of refrigerant flows to be used easily as a parameter in the tests. The lack, to our knowledge, of reliable and detailed experimental information in this application has been another factor in favour of this decision. The large size of the evaporators makes difficult the experimentation in real scale and has forced engineers to extrapolate available experimental results and combine empirical experience in their design and sizing. On the other hand, well validated numerical models of this equipment would give possibility for considerable cost and material savings through optimization. Having the liquid overfeed system as a basis, it would not be difficult to create a direct expansion circuit, but this decision has been let for the future.

The test prototype was decided to be installed in a climatic chamber regulating the inlet air temperature and humidity. The climatic chamber would also give the possibilities to use the infrastructure for other purposes, as refrigerated room air convection, air curtain experiments, etc.

The numerical simulation models have been essential for assisting the design of the experimental infrastructure. For the determining of the working range of the liquid refrigerant circuit the simulation of the tested prototype has been used together with the conjunct simulation of the whole circuit. This has given basis and guidelines for control strategies and the selection of appropriate control hardwear. The evaporator modelling and the simulation of the liquid overfeed refrigeration system have been essential for the sizing of the system's components. It has permitted to design the system and the controls in order to fulfil the previously assigned requirements for working range and sizing of the experimental prototype for the desired working range.

In the development of the experimental infrastructure fundamental task has been the selection of appropriate measuring instrumentation, allowing to produce quality experimental results. The previous uncertainty analysis of the experimental measurements, with the adopted conceptual design, has proven the capability of the experimental facility to fulfil the proposed objectives. The analysis showed that temperature measurements are critical for the obtaining of accurate cooling capacity of the tested prototypes. Resistive thermal devices (RTD, Pt100) have been selected for the temperature measurement of the refrigerant, because of their accuracy and stability. Important conclusions have been made about the size of the used intermediate plate heat exchangers, and bigger size than the initially planned were selected in order to permit the desired heat through them to be exchanged with lower flows, permitting higher temperature lifts in the fluids. For the measurement of the air temperatures thermo-couples type-K have been selected from size and accuracy considerations, giving the possibility for their distributed mounting in the air cross-section of measurement. In order to assure additional checking of this measurement, and in cases when non-uniform air velocities are present over the section of measurement, a mixing section down-stream of the test prototype air-side has been designed, with mixed air temperature measurement using RTD. Refrigerant and air-flow measurements have also shown to be important for the quality of the measured result. Coriolis type mass flow-meters have been selected for the refrigerant flow measurement, being those the most accurate. Insertion thermal mass flow-meter, factory calibrated for the desired range with a flow homogenizer (vortab), has been selected for the air-flow measurement. The condition of the refrigerant at the inlet of the evaporator is critical for the determining of its cooling capacity and the correct comparison of the experimental and numerical results, being a boundary condition for the numerical simulation. The refrigerant condition at this point is based on enthalpy determination through the measurement of temperature and absolute pressure. Quality absolute pressure transducer have been selected for this measurement.

An electronic data acquisition system has been developed in order to accommodate the measured variables, fulfilling the requirements for accuracy and stability. All the measured variables are acquired and recorded on PC, using especially developed for this purpose software program. The obtained experimental information is automatically processed and analysed with a Perl based program, created and adapted for each experimental situation and objective. Different modules within the program are dedicated to obtaining of the result from the measured variables, the detailed uncertainty analysis, the experimental verification balance checks and the comparison of the experimental and numerical results. The program generates extensive output in tabular form and data files in format appropriate for generation of numerous different graphical representations. The analysis involves statistic evaluation of the experimental results and the experimental-numerical comparisons as a whole and for groups of results divided according to selected criteria, and is the basis of the proposed validation methodology.

References

[1] F.S. Rowland and M.R. Molina. Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom Catalyzed Destruction of Ozone. *Nature*, vol.249:pp.810–812, 1974.

[2] Unated Nations Environmental Programme (UNEP). Montreal protocol on substances that deplete the ozone layer, 1987.

[3] Unated Nations Framework Convention on Climate Change (UNFCCC). Kyoto protocol, 1997.

[4] Escanes F., Pérez-Segarra C. D., and Oliva A. Thermal and fluid-dynamic behaviour of double-pipe condensers and evaporators. *International Journal of Numerical Methods for Heat and Fluid Flow*, vol.5(no.9):pp.781–795, 1995.

[5] Escanes F., Pérez-Segarra C. D., and Oliva A. Numerical simulation of capillary-tube expansion devices. *International Journal of Refrigeration*, vol.18(no.2):pp.113–122, 1995.

[6] Pérez-Segarra C.D., Escanes F., and Oliva A. Numerical study of the thermal and fluid dynamic behaviour of reciprocating compressors. In *International Compressor Engineering Conference, Purdue University, IN, USA*, pages 145–150, 1994.

[7] García-Valladares O., Pérez-Segarra C.D., Rigola J., and Oliva A. Detailed numerical simulation of condensers and evaporators using pure and mixed refrigerant. In *International Compressor Engineering Conference at Purdue*, volume 2, pages 839–844, 1998.

[8] Oliet C., Pérez-Segarra C.D., García-Valladares O. Ordoñez R., and Sudrià J. Diseño termo-fluídico de intercambiadores compactos gas-líquido. Aplicación a radiadores de automoción y evaporadores. In *Anales de Ingeniería Mecánica. XIII Congreso Nacional de Ingeniería Mecánica, Terrassa*, volume 4, 1998.

[9] Oliet C., Pérez-Segarra C.D., García-Valladares O., and Oliva A. Advanced Numerical Simulation of Compact Heat Exchangers. Application to Automative, Refrigeration and Air-Conditioning Industries. In *Proceedings of the European Congress on ComputationalMethods in Applied Sciences and Engineering (ECCOMAS)*, Barcelona, 2000.

[10] Oliet C., Pérez-Segarra C.D., Danov S., and Oliva A. Numerical Simulation of Dehumidifying Fin-and-tube Heat Exchangers. Model Strategies and Experimental Comparisons. In *Ninth International Refrigeration and Air Conditioning Conference at Purdue*, 2002.

[11] Patric J. Roache. *Verification and Validation in Computational Science and Engineering.* Hermosa Publishers, 1998.

[12] U. Mehta. Guide to Credible Computational Fluid Dynamics Simulations, AIAA Paper 95-2225. June 1995.

[13] Joseph G. Marvin. Perspective on computational fluid dynamics validation. *AIAA*, 33(10):1778–1787, October 1995.

[14] H.W.Coleman. Uncertainty Considerations in Validating CFD Codes with Experimental Data, AIAA Paper 96-2027. In *New Orleans, Louisiana Conference*, June 1996.

[15] García-Valladares O., Pérez-Segarra C.D., Oliet C., and Danov S. Numerical Studies of Refrigerating Liquid Overfeed Systems Working with Ammonia and R134a. In *International Refrigeration and Air Conditioning Conference at Purdue*, volume 1, pages 327–334, 2000.

[16] X. Jia, C.P. Tso, and P.K. Chia. A distributed model for prediction of the transient response of an evaporator. *Int. J. Refrig.*, vol.18(no.5):pp.336–342, 1995.

[17] A. Bensafi, S. Borg, and D. Parent. CYRANO: a computational model for detailed design of plate-fin-and-tube heat exchangers using pure and mixed refrigerants. *Int. J. Refrig.*, vol.20(no.3):pp.218–228, 1997.

[18] T.T. Chow. Chilled water cooling coil models from empirical to fundamental. *NHTA*, vol.32:pp.63–83, 1997.

[19] H.W. Wang and S. Touber. Distributed and non-steady state modelling of an air cooler. *Int. J. Refrig.*, vol.14(no.2):pp.98–111, 1991.

[20] ARI Standard 410-2001: Forced Circulation Air-Cooling and Air-Heating Coils, Arlington, VA, U.S.A., 2001.

[21] ANSI/ASHRAE Standard 33-2000: Methods of Testing Forced Circulation Air Cooling and Air Heating Coils, ASHRAE, 1791 Tullie Circle, N.E., Atlanta, GA 30329, U.S.A., 2000.

[22] S.Y. Liang, T.N. Wong, and G.K. Nathan. Numerical and experimental studies of refrigerant circuitry of evaporator coils. *Int.J.Refrig.*, vol.24(no.8):pp.823–833, 2001.

[23] A.I. ElSherbini, A.M. Jacobi, and P.S. Hrnjak. Experimental investigation of thermal contact resistance in plain-fin-and-tube evaporators with collarless fins. *Int.J.Refrig.*, vol.26(no.5):pp.527–536, 2003.

[24] Man-Hoe Kim and Clark W. Bullard. Air-side thermal hydraulic performance of multi-louvered fin aluminium heat exchangers. *Int.J.Refrig.*, vol.25(no.3):pp.390–400, 2002.

[25] Man-Hoe Kim, Sumin Song, and Clark W. Bullard. Effect of inlet humidity condition on the air-side performance of an inclined brazed aluminium evaporator. *Int.J.Refrig.*, vol.25(no.5):pp.611–620, 2002.

[26] Jangho Lee, Young-Chul Kwon, and Moo Hwan Kim. An improved method for analyzing a fin and tube evaporator containing a zeotropic mixture refrigerant with air mal-distribution. *Int.J.Refrig.*, vol.26(no.6):pp.707–720, 2003.

[27] Wei-Mon Yan and Pay-Jen Sheen. Heat transfer and friction characteristics of fin-and-tube heat exchangers. *Int.J.Heat Mass Transfer*, vol.43:pp.1651–1659, 2000.

[28] Metin Tuztas. Mathematical model of finned tube heat exchangers for thermal simulation software of air conditioners. *Int.Comm.Heat Mass Transfer*, vol.29(no.4):pp.547–556, 2002.

[29] ANSI/ASHRAE Standard 41.2-1987: Standard methods for laboratory air-flow measurement, 1987.

[30] J. Chi and D. Didion. A simulation model of the transient performance of a heat pump. *Int.J.Refrig.*, vol.5(no.3):pp.176–184, 1982.

[31] W.E. Murphy and V.W. Goldschmidt. Cyclic characteristics of a typical residential air conditioner - modeling of start-up transients. *ASHRAE Transactions*, vol.91(no.2):pp.427–444, 1985.

[32] W.E. Murphy and V.W. Goldschmidt. Cyclic characteristics of a typical residential air conditioner - modeling of shutdown transients. *ASHRAE Transactions*, vol.92(no.1):pp.186–202, 1986.

[33] N. Rajendran and M.B. Pate. A computer model of the start-up transients in a vapor compression refrijeration system. *Progress in the Design and Construction of Refrigeration Systems, ed. by D.R.Tree*, pages 129–140, 1986.

[34] J.W. MacArthur. Transient heat pump behaviour: a theoretical investigation. *Int.J.Refrig.*, vol.7(no.2):pp.123–132, 1984.

[35] D.S. Jung and R. Radermacher. Performance simulation of a single-evaporator domestic refrigerator charged with pure and mixed refrigerants. *Int.J.Refrig.*, vol.14:pp.223–232, 1991.

[36] X. Yuan and D.L. O'Neal. Development of a transient simulation model of a freezer. Part I: Model development. *1994 International Refrigeration Conference at Purdue*, pages 213–224.

[37] F. Escanes, A. Oliva, C.D. Pérez-Segarra, and F.J. Flores. Numerical simulation of a single stage vapour compression refrigerating unit. *International Compressor Engineering Conference, Purdue University, IN, USA*, pages 139–144, 1994.

[38] J. Rigola, F. Escanes, A. Oliva, and C.D. Pérez-Segarra. Numerical study of a single vapour compression refrigerant unit using non-contaminant refrigerants. *International Compressor Engineering Conference, Purdue University, IN, USA*, pages 77–82, 1996.

[39] J. Rigola, C.D. Pérez-Segarra, O. García-Valladares, J.M. Serra, M. Escribà, and J. Pons. Numerical study and experimental validation of a complete vapour compression refrigerating cycle unit. *International Refrigeration Conference, Purdue University, IN, USA*, pages 201–206, 1998.

[40] J. Khan and S.M. Zubair. Design and performance evaluation of reciprocating refrigeration systems. *Int.J.Refrig.*, vol.22:pp.235–243, 1999.

[41] R.N.N. Koury, L. Machado, and K.A.R. Ismail. Numerical simulation of a variable speed refrigeration system. *Int.J.Refrig.*, vol.24:pp.192–200, 2001.

[42] G. Giuliani, N.J. Hewitt, F. Marchesi Donati, and F. Polonara. Composition shift in liquid-recirculation refrigeration systems: an experimental investigation for pure fluid r134a and the mixture r32/134a. *Int.J.Refrig.*, vol.22:pp.486–498, 1999.

Stoyan Viktorov Danov, *Development of experimental and numerical infrastructures for the study of compact heat exchangers and liquid overfeed refrigeration systems,* Doctoral Thesis, Universitat Politècnica de Catalunya, November 2005.