# Chapter 6

# Conclusions and future actions

## 6.1 Concluding remarks

Experimental infrastructure has been developed with the objective of experimental validation of mathematical models in the field of refrigeration and air conditioning. The initially proposed scope has been the experimental study of compact heat exchangers and liquid overfeed refrigeration systems, in well established geometrical and boundary conditions, permitting the unequivocal comparison of the experimental data with numerical predictions of the previously developed mathematical models, [1], [2], [3], presented in chapter 2. Nevertheless, the design has been conceived having in mind the possible future expansion of the facilities to other applications, as direct expansion evaporators testing, frost formation over heat exchangers, air convection studies in rooms, air curtain testing, etc.

Functionality and flexibility have been sought through the design decisions. The developed refrigerant circuits have been interrelated to maximally use the available instrumentation and controls. The liquid refrigerant circuit has been used as a separate test circuit, and to control the condenser secondary fluid inlet conditions. This has given the possibility to control and measure the heat transfer of the liquid overfeed refrigeration system with the exterior, and to verify the experimental measurements in the evaporator and the condenser through energy balance checks, using independent measurements of the same physical quantity.

In the phase-changing circuit a direct connection between the evaporator and the condenser has been implemented, decoupling the testing of liquid overfeed evaporators from the compressor limitations, expanding considerably the capabilities of the experimental facility and its working range.

The design of the experimental infrastructure has been widely assisted with numerical simulations, through which the possible working range has been determined, and the

selection of the components integrating the set up has been facilitated.
The design of the infrastructure in a large extent has been conditioned by the methods for determining of the indirect measuring results: mainly the cooling capacity of the tested heat exchanger. The objective has been to achieve reasonable accuracy of this measurement, in order it to serve for experimental validation of the numerical models. A preliminary uncertainty analysis has helped to detect the critical measuring variables, which accuracies affect in greater extent the accuracy of the result, and to select for them the most appropriate measuring instruments. Generally, these have proven to be the temperature and the mass flow measurements.
All the measuring instruments have been calibrated to the range of the measured variables. Most of them have been factory calibrated. The temperature sensors (RTD, TC) have been calibrated in the CTTC, in a thermostatic bath versus precision thermometer as a standard. Being these the most important measurements in the experiment, special attention has been paid to their calibration. They have been calibrated in the whole measuring range for each sensor, in steps of $5^oC$. A special procedure has been developed for the evaluation of the remaining temperature measurement uncertainty after calibration. This has been done experimentally, comparing the measurements of the temperature sensors after calibration with the measurements of the precision thermometer in a controlled ambient. The evaluation of the systematic uncertainty of the sensors involves the maximum difference found in the calibrated range between their measurement and the measurement of the precision thermometer, and the standard deviation of that difference, as exposed in section 4.3.
Special importance has been given to the uncertainty analysis, as a basic requisite of the experimental data. The individual instrument uncertainties, the data acquisition uncertainties and the uncertainties introduced from the process control stability have been considered. Their combining in the data reduction equation to obtain the uncertainty of the result has been analysed, see section 4.5.
For the data processing software tools have been specially developed. The considerable amount of experimental data has been processed automatically to obtain the indirect experimental results, to carry out the uncertainty analysis, and to perform the numerical to experimental comparisons. In order to guarantee numerical results at the exactly the same experimental conditions, a software program has been created to generate the input files for the numerical simulations directly from the experimental results.
Experimental results obtained with the developed infrastructure have been presented. Detailed studies of compact heat exchangers under cooling conditions, using liquid and phase-changing refrigerants, have been performed and presented. Results from the experimental studies of the liquid overfeed refrigeration system have been also presented. The results have been checked for consistency through energy balance checks for all the components where measurements of the same physical magnitude

can be contrasted with independent measurements. Detailed geometrical description of the tested compact heat exchangers is provided, and in order to give more general use of the obtained experimental data, the raw experimental information comprising all the measured variables during the tests is presented.
An experimental validation methodology for the compact heat exchanger model CHESS (see chapter 2) has been suggested, 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 give global evaluation of the numerical model performance in the tested conditions. An extensive tabular and graphical comparisons have been presented. The validation methodology proposed for the heat exchanger model can be used as a basis for validation of numerical models in general.

## 6.2 Future actions

The work initiated in this thesis can be continued in various directions that may be generally classified as experimental infrastructure improvement and development, and experimental validation methodology and performance. This future work can expand the scope of the experimental studies and complete the validation of the mathematical models.
The improvements and the further development of the experimental infrastructure can be summarized in the following guidelines.

- Preparation of the experimental facilities for testing compact heat exchangers under frosting conditions. This implies modifications permitting the measuring of the frost accumulation over the fins of the tested heat exchanger when the refrigerant temperature is below the water freezing point. Changes in the design of the heat exchanger test section must be implemented to accommodate the frost formation, and measures assuring defrosting must be taken.
  An application of electronic scales for measuring the weight of the test section has been considered for measuring of the frost accumulation rate. This can be done in the tests with liquid refrigerant, where the mass of the refrigerant in the heat exchanger is almost invariable, and the small changes that occur can be quantified from the temperature and density relations. In the case of liquid overfeed evaporators testing, the problem is complicated from the possible changes of the refrigerant mass in the evaporator with the changes of the evaporating rate, and there the solutions may be searched in global terms, measuring the defrosted condensate quantity.

- Adaptation of the infrastructure for testing of air-heating prototypes and automotive radiators. This implies modifications in the air-handling circuit and the liquid circuit. In order to assure proper control at the inlet of the tested

heat exchanger under heating conditions, a cooling should be provided in the compensating chamber. If standard automotive radiators are tested, due to the high heating capacity of these equipment, it may not be feasible to use a closed air loop. In this case is more practical to precondition outside air in the compensating chamber and release the heated outlet air to the ambient.
In the liquid circuit the adaptation implies addition of a heating source. A gas heated boiler has been considered for this application.

- Modifications of the phase-changing circuit permitting the testing of direct expansion evaporators and systems. This can be done introducing the necessary changes in the refrigerant lines in order to assure the proper functioning of the system in this mode.

The future work concerning the experimental validation methodology and studies can be summed up in the following items.

- Developing of experimental validation methodology for the liquid overfeed refrigeration system model. This requires the generation of the input for the numerical simulations directly from the experimental data, assuring comparisons at the exactly same conditions. The methodology must be based on systematic comparisons between the numerical and experimental results and the statistical analysis of the differences in order to permit clear conclusions to be made. Appropriate graphical comparisons should be searched for visual qualitative assessment of the results.

- Extensive validation studies of the compact heat exchanger model using the proposed methodology. Different levels of numerical modelling, and use of different empirical correlations for the heat transfer coefficient air- and refrigerant-side should be carried out, in order to determine the most appropriate modelling for the experimentally studied range.

# References

[1] 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.

[2] 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.

[3] 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.