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Experimental study of an air-source heat pump for simultaneous heating and cooling – Part 1: Basic concepts and performance verification

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ABSTRACT

This article presents the concepts of an air-source Heat Pump for Simultaneous heating and cooling (HPS) designed for hotels and smaller residential, commercial and office buildings in which simultaneous needs in heating and cooling are frequent. The main advantage of the HPS is to carry out simultaneously space heating and space cooling with the same energy input. Ambient air is used as a balancing source to run a heating or a cooling mode. The second advantage is that, during winter, energy recovered by the subcooling of the refrigerant is stored at first in a water tank and used subsequently as a cold source at the water evaporator to improve the average performance and to carry out defrosting of the air evaporator using a two-phase thermosiphon. Unlike conventional air-source heat pumps, defrosting is carried out without stopping the heat production. A R407C HPS prototype was built and tested. Its performance on defined operating conditions corresponds to the data given by the selection software of the compressor manufacturer. The operation of the high pressure control system, the transitions between heating, cooling and simultaneous modes and the defrosting sequence were validated experimentally and are presented in the second part of this article [1].

Keywords: *heat pump, heating, cooling, thermosiphon, defrosting*

NOMENCLATURE

AHX air heat exchanger

C-mode cooling mode

H-mode heating mode

HP	high pressure (Pa)
HPS	heat pump for simultaneous heating and cooling
LP	low pressure (Pa)
\dot{Q}	heating or cooling capacity (W)
r	ratio (-)
S-mode	simultaneous mode
T	temperature (°C)

Subscripts:

aEv	air evaporator
c	cooling
CD	condensation
d	demand
EV	evaporation
exp	experimental
h	heating
mod	modelled
p	production
wEv	water evaporator

1 Context and objectives

Energy efficiency of buildings is continuously improving thanks to more and more stringent thermal regulations. Besides, comfort requirements demand more and more energy. The demand for cooling is rising to compensate internal heat gains caused by more and more household electrical equipment whilst domestic hot water (DHW) demands continue to increase. A better thermal envelope implies less energy for heating and more for cooling. Therefore thermal needs of new buildings follow the trend of more balanced energy demands between heating and cooling. ECBCS Annex 48 of the International Energy Agency deals with this issue [2]. An answer to a simultaneous energy demand in heating and cooling is the heat pump, since it has simultaneously a heating capacity at the condenser and a cooling capacity at the evaporator.

This study presents the design of a heat pump that can satisfy fluctuating needs, simultaneous or not, in heating and cooling. This heat pump with heat recovery is named HPS (Heat Pump for Simultaneous heating and cooling). It is suited to buildings such as hotels where DHW demands are high, small commercial units like

groceries and petrol stations or glass-fronted north-south oriented office buildings where simultaneous needs in space heating and cooling are frequent.

The first objective of the HPS is to produce, as often as possible, heating and cooling energies using the same electric energy input at the compressor. Chua et al. [3] evocate a significant reduction in carbon footprint using improved heat pumps for heating and cooling. Many authors work on such systems for simultaneous production in various applications. For example, Liu and Hong [4] compare ground source heat pumps to variable refrigerant flow systems, both able to provide heating and cooling energies to four perimeter zones and one core zone of a simulated small office building. White et al. [5] expose the advantageous performance of a transcritical CO₂ heat pump for simultaneous refrigeration and water heating. Gong et al. [6] present an air-conditioning/heat-pump system recovering heat for domestic hot water production. All these heat pumps demand more research and development but consume less energy than conventional systems.

The second objective is to propose an answer to reduce the performance loss of air-source heat pumps during winter. This aspect depends on the dynamic behaviour of the HPS which is dealt with in part 2 of this article [1]. A HPS prototype was built and tested. The aim of the first part of the study is to verify that the performance in each mode of operation (heating, cooling and simultaneous modes) is correct.

2 HPS concepts

2.1 Components

The HPS prototype (Fig. 1) produces hot and chilled water using plate heat exchangers. A balancing air coil works either as a condenser for heat rejection in a cooling mode or as an evaporator for heat suction in a heating mode. The air evaporator and the air condenser are never used at the same time. These functions have been assembled in the same three-fluid air coil (air, high pressure refrigerant and low pressure refrigerant) in order to decrease the finned surface area compared to separate air condenser and evaporator. When the tubes of the air evaporator are used the surface of the fins near the tubes of the air condenser are also used and vice versa. A subcooler is connected to the cold water loop to carry out a short-time heat storage during winter sequences. Depending on the mode of operation, the electric components (compressor, fan and electronic valves named Evr) are managed automatically by a programmable controller or manually by the operator. The thermostatic expansion valves are named TEV1 (connected to the water evaporator) and TEV2 (connected to the air evaporator). Table 1 shows the general specifications of the components. The chosen refrigerant is R407C,

which is widely used in heat pumping technology. Non-return valves named Nrv1 and Nrv2 are placed at the outlets of the air and water condensers.

2.2 Operating modes

Three operating modes can be run.

- The simultaneous mode produces hot and cold water using the water condenser and the water evaporator (electronic valves Evr1 and Evr3 are open).
- The heating mode produces hot water using the water condenser, the air evaporator (electronic valves Evr2 and Evr3 are open) and also the subcooler to store the subcooling energy in the cold water tank.
- The cooling mode only produces cold water using the water evaporator and the air condenser (electronic valves Evr1 and Evr4 are open).

A production ratio r_p can be defined following Eq. (1) using heating and cooling capacities. For a simultaneous production mode this ratio is close to 1.3.

$$r_p = \frac{\dot{Q}_h}{\dot{Q}_c} \quad (1)$$

A demand ratio r_d can be defined following Eq. (2) using integrated heating and cooling demands.

$$r_d = \frac{\text{heating demand}}{\text{cooling demand}} \quad (2)$$

Depending on the building's demand ratio r_d , two sequences can be run:

- if $r_d > r_p$, heating demand is higher than cooling demand, the sequence starts in the simultaneous mode and continues in the heating mode when the cooling demand is satisfied;
- if $r_d < r_p$, cooling demand is higher than heating demand, the sequence starts in the simultaneous mode and continues in the cooling mode when the heating demand is satisfied.

The variability of operating times in each mode enables the control system to adapt hot and chilled water production to heating and cooling demands.

2.3 High pressure control

The high pressure control system is based on the temperature control of refrigerant in a liquid receiver. High pressure is controlled depending on the hot source temperature. The whole operation is described in the second article on this work concerning the dynamic behaviour [1].

2.4 Comparison between the HPS and a standard reversible heat pump

The HPS is able to produce simultaneously hot and cold water whereas the standard reversible heat pump cannot. Over a year, if the simultaneous demand in heating and cooling is important, using a heat pump with heat recovery such as the HPS enables to achieve substantial energy savings. If not, the reversible heat pump would be the best techno-economical choice.

The HPS heat exchangers and connexions are sized and optimized, each of them for a unique application. For example, the water evaporator will never be used as a water condenser. This is not the case for standard reversible heat pumps: heat exchangers efficiencies and thus overall performance usually decrease in the reversed mode [7].

Because the HPS components are dedicated either to evaporation or condensation, pressures vary in a smooth manner during transitions between modes. The longevity of the HPS compressor is increased compared to the one of the reversible heat pump subjected to important mechanical strains during switches of the reversing valve. The operations of the HPS and a standard reversible air-to-water heat pump installed in a hotel of 45 bedrooms situated in Rennes were analyzed in yearly simulations using Trnsys software [8,9]. Both plants were equipped with electric auxiliary heaters and produced heating and cooling energy for space heating, space cooling and DHW production. The results showed an annual electric energy saving of 19.8%. The annual performance improvement of the HPS reached 16.6%. These interesting results were obtained thanks to the simultaneous mode of production, to the use of the cold water tank as a short-time heat storage during winter sequences for performance enhancement and to the two-phase thermosiphon defrosting technique.

3 Experimental study

3.1 Experimental setup

A HPS prototype was built and connected to a water distribution system (Figs. 2 and 3). The water system is used to limit the temperature variation of hot and cold water. It is composed of two water tanks, a circulation pump and four fan coil units (FCU) that dissipate the heating or cooling energy produced by the heat pump. The heating and cooling nominal power of the FCU is respectively 1.85 kW (50°C/40°C) and 1.5 kW (7/12°C). Temperature and humidity of the air circulating through the AHX are controlled, namely in order to obtain frosting conditions at the air coil.

Type K thermocouples were placed on every inlet and outlet of the refrigeration cycle components on refrigerant, water and air sides. All thermocouples, (for example the ones giving $T_{hot\ gas}$, T_{aEv} and T_{wEv} , shown in Fig. 1) were placed in contact with the copper tubes and recovered by a lagging tape. The uncertainty on these

measurements is ± 0.5 K. High and low pressure sensors come from the P299 series of Johnson Controls. Their accuracy is $\pm 1\%$. The sensors were connected to an acquisition unit using a time base of 1 second and to the control computer through which were also managed the different electric devices. Electric energy consumption was given by a pulse electric meter. Water mass flow rates were calculated using water meters.

3.2 Performance verification

The performance of the HPS in terms of instantaneous COP was assessed during operations in heating, cooling and simultaneous modes. The COP is defined by the ratio of thermal capacity over electric power input at the compressor. In the simultaneous mode, heating and cooling capacities are summed. Refrigerant superheating is taken into account. Thermal capacities are calculated for a 0 K subcooling. Tables containing the results of COP calculations displayed in Figs 4 to 6 are available in the appendix for each test in the different modes. For each measurement, these tables also present the corresponding evaporating temperature, condensing temperature and superheat.

Figs. 4 to 6 show the COPs of the HPS prototype in heating, cooling and simultaneous modes in proportion to modelled COPs. The modelled COPs are calculated using the selection software of the compressor manufacturer depending on condensing and evaporating temperatures, useful superheat (in the evaporator) and subcooling. Minimum suction superheat admitted by the software is 4 K. This suction superheat value was taken for the model. The uncertainty of the model is 5%. The sensibility of sensors and counters produce uncertainties on the measurements of thermal capacity and electric power of respectively 3.72% and 0.33%. However, results show discrepancies up to 15% between experimental and modelled values for the lower values of COPs. The lower values of COPs appear for the higher differences between the temperatures of hot and cold sources. This means that the difference between operating temperatures and the ambient temperature of the laboratory is higher. In spite of the attention paid to setting up the sensors and isolating them thermally, the metrology only guarantee an uncertainty interval of 15%. Nevertheless, it is sufficient to state that the special tubing of the circuit does not affect the heat pumping performance.

The variation of the composition of the refrigerant mixture R407C influences the system performance. The presence of a liquid receiver can cause a more important modification of the refrigerant composition and an increased COP reduction [10]. Figs. 4 to 6 show that this effect is not significant for the HPS.

4 Conclusions

This article presents the design of an air-source heat pump for simultaneous heating and cooling (HPS) that offers improved performance compared to standard reversible heat pumps. Apart from producing simultaneously

hot and cold water, the configuration enables to switch from the air evaporator to a water evaporator during winter sequences. This machine proposes an answer to reduce the performance loss of air-to-water heat pumps under low ambient temperatures by the use of operating sequences alternating between an air evaporator and a water evaporator. Moreover, while standard air-source reversible heat pumps are penalized by defrosting (break in the heat production, decrease in COP), the HPS carries out defrosting using a two-phase thermosiphon with increased heat pump performance. Thanks to the special management of produced energies, simulations showed an annual performance increase of 16.6% when comparing the HPS to a standard reversible heat pump [9]. The HPS performance was verified in the three operating modes: heating only, cooling only and simultaneous heating and cooling, by comparison with the selection software of the compressor manufacturer. In part 2 of this article [1], the phenomenology of the HPS operation is studied on a dynamic point of view. The concepts of high pressure control, transitions between modes and the two-phase thermosiphon defrosting technique are analysed and validated experimentally.

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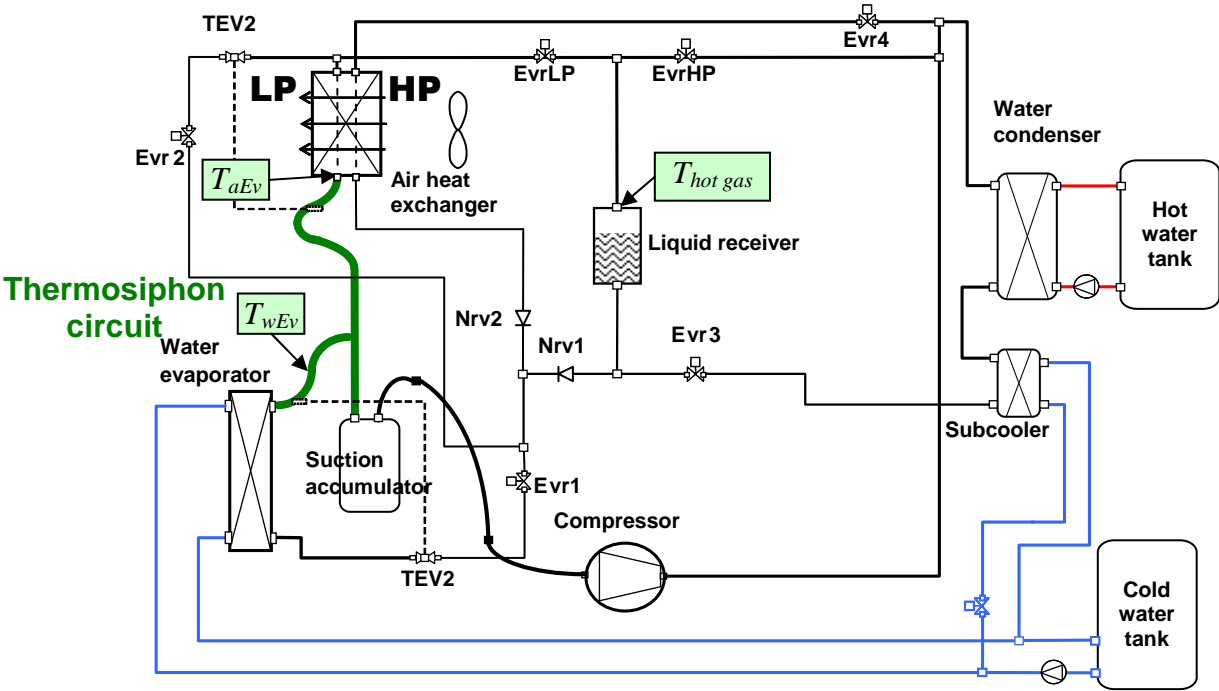


Fig. 1. HPS circuit

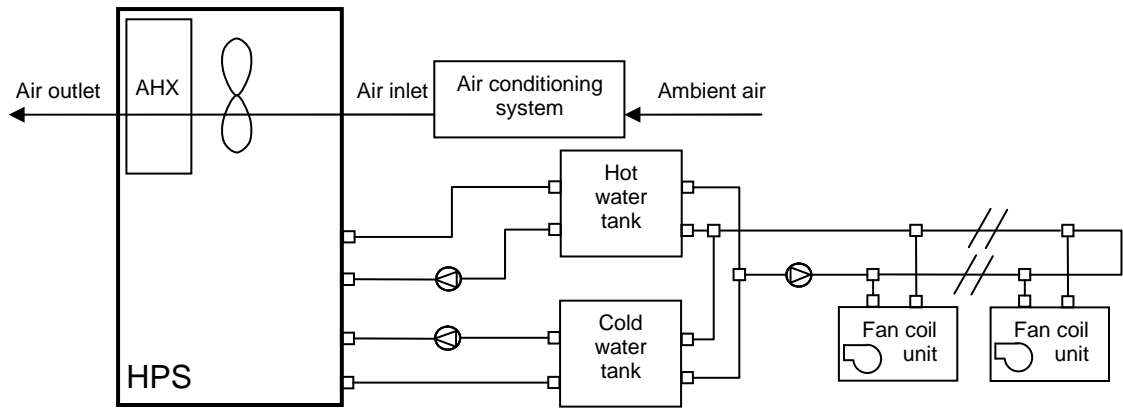


Fig. 2. Scheme of the connections of the HPS to air and water systems



Fig. 3. Photograph of the experimental setup

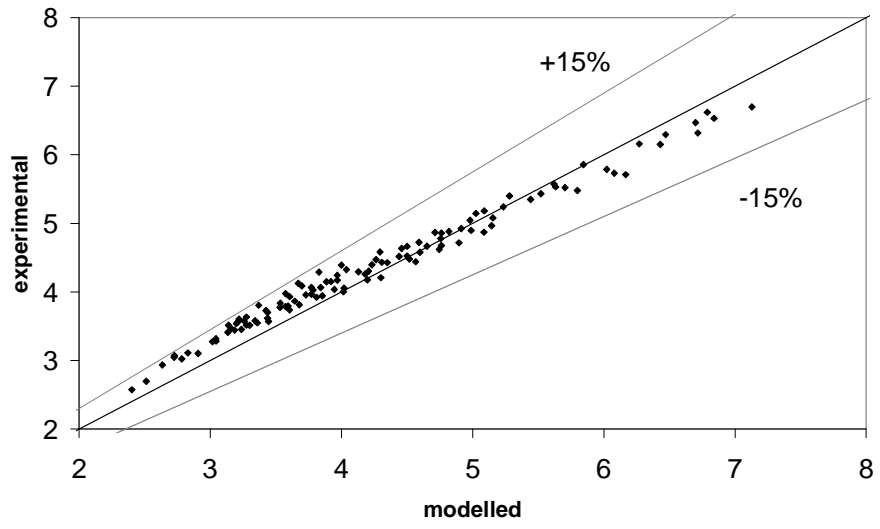


Fig. 4. Heating COP in the heating mode

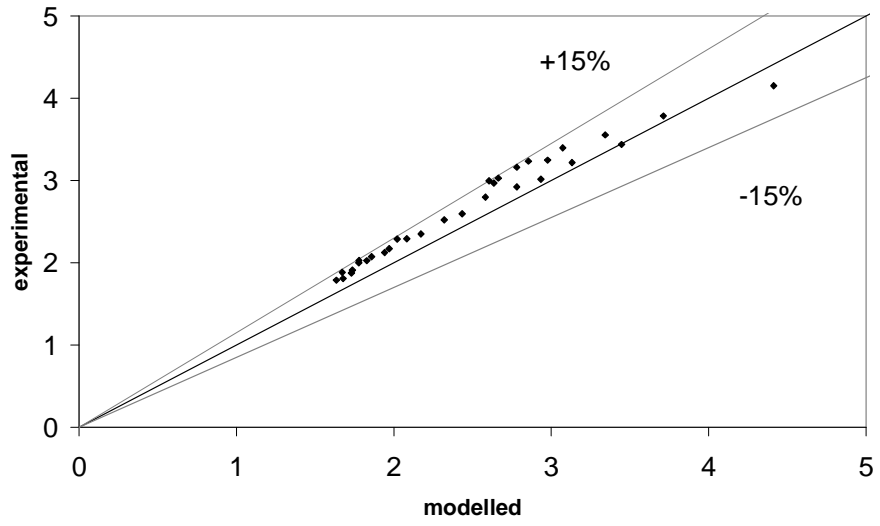


Fig. 5. Cooling COP in the cooling mode

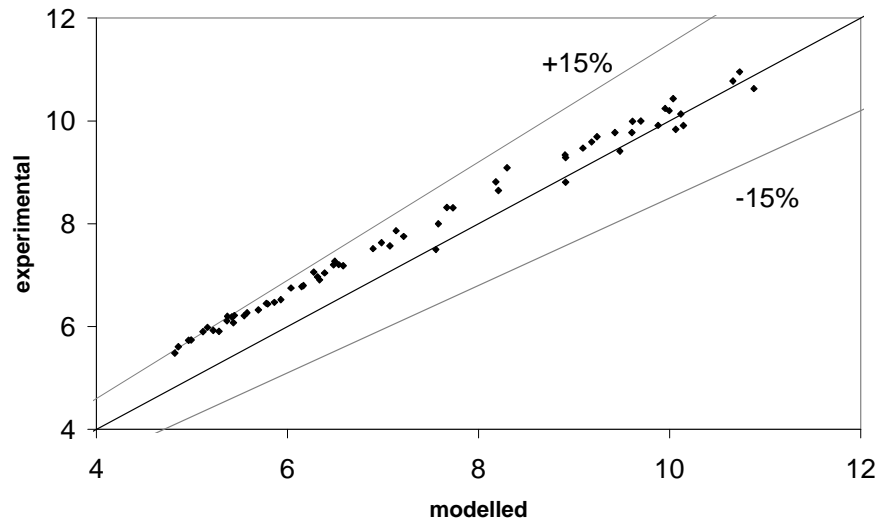


Fig. 6. Heating and cooling COP in the simultaneous mode

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Component	Specification
Compressor Brand: Copeland Type: Scroll Ref: ZB38KCE-TFD	Swept volume: 14.5 m ³ /h Nominal cooling capacity (T _{ev} = 0°C / T _{cd} = 40°C): 11.5 kW
Water heat exchangers - condenser - evaporator - subcooler	Type: plate heat exchanger 50 plates, 2.45 m ² 34 plates, 0.8 m ² 14 plates, 0.16 m ²
Air heat exchanger	Type: finned tubes, 68 m ² 6 rows of 30 tubes (l = 750 mm , Ø = 10 mm)
Working fluid	R407C

Table 1. Specifications of HPS components

Appendix: Results of experimental and modelled COP calculations for performance verification

Test	superheat (°C)	T _{EV} (°C) (dew point)	T _{CD} (°C) (dew point)	COP _{exp}	COP _{mod}
	2.8	0.5	36.7	4.87	5.09
	2.1	-1.4	36.8	4.78	4.76
	4.7	-1.2	37.1	4.68	4.76
	4.7	-1.6	37.8	4.58	4.60
	2.1	-1.7	38.3	4.48	4.52
	3.5	-1.3	39.0	4.53	4.50
	1.5	-2.0	39.8	4.43	4.31
	2.6	-1.5	41.3	4.18	4.20
	2.3	-1.4	41.4	4.30	4.21
	1.1	-2.0	43.0	4.04	3.95
	3.1	-1.2	43.2	4.06	4.02
	1.5	-1.7	43.9	4.15	3.89
H-mode n°1	1.3	-1.6	44.3	3.94	3.85
	2.2	-1.4	45.1	3.92	3.81
	1.0	-1.8	46.6	3.74	3.60
	2.0	-1.4	47.1	3.80	3.59
	1.3	-1.3	47.9	3.78	3.53
	1.0	-1.7	49.3	3.55	3.36
	2.3	-1.4	49.8	3.58	3.34
	2.7	-1.2	50.5	3.51	3.30
	1.5	-1.3	51.1	3.45	3.24
	1.9	-1.2	51.8	3.44	3.19
	0.9	-1.7	52.9	3.28	3.05
	1.7	-1.2	53.5	3.32	3.04
	1.4	-1.2	55.2	3.10	2.91
	2.0	1.6	40.0	4.88	4.82
	1.1	-2.1	40.0	4.47	4.26
	1.2	-4.3	40.0	4.24	3.97
	1.3	-5.7	40.0	4.03	3.78
	1.5	-6.9	40.0	3.87	3.64
	1.4	-7.8	40.0	3.84	3.53
	1.2	-8.7	40.0	3.73	3.42
	1.6	-10.0	40.0	3.63	3.28
	1.1	-10.6	40.0	3.60	3.22
H-mode n°2	0.6	-11.3	40.0	3.51	3.14
	0.3	-11.4	45.0	3.02	2.78
	0.7	-12.1	45.0	3.07	2.73
	1.6	-10.9	45.0	3.11	2.83
	2.6	-7.6	45.0	3.41	3.13
	4.7	-4.6	45.0	3.62	3.44
	5.4	-2.5	45.0	3.81	3.68
	4.4	-1.7	45.0	3.97	3.77
	3.7	-1.2	45.0	4.06	3.84
	4.8	-0.5	45.0	4.15	3.92
	4.7	0.2	45.0	4.01	4.02
	7.5	4.8	30.6	6.62	6.79
	10.1	5.0	41.6	4.96	5.14
	9.4	4.7	42.3	4.90	4.99
	8.0	5.0	43.4	4.72	4.90
H-mode n°3	7.5	4.4	43.8	4.62	4.74
	8.0	4.8	45.6	4.44	4.57
	8.1	4.9	46.3	4.67	4.50
	9.8	5.4	48.0	4.43	4.35
	10.1	5.5	49.6	4.26	4.18

Test	superheat (°C)	T _{EV} (°C) (dew point)	T _{CD} (°C) (dew point)	COP _{exp}	COP _{mod}
	7.8	1.8	24.7	6.70	7.13
	8.1	1.7	26.4	6.53	6.84
	8.5	2.0	27.6	6.32	6.72
	8.2	2.2	27.9	6.47	6.70
	8.0	1.7	28.7	6.29	6.47
	8.3	2.2	29.6	6.15	6.43
	7.4	1.9	30.3	6.16	6.27
	7.7	1.8	31.4	5.73	6.08
	7.9	2.0	32.0	5.79	6.02
	7.1	1.6	32.9	5.48	5.80
	7.3	1.7	33.8	5.52	5.70
	6.6	1.9	34.6	5.57	5.62
	6.7	1.9	35.3	5.43	5.52
	7.2	2.0	36.0	5.35	5.44
	5.3	1.6	36.9	5.24	5.23
	5.6	1.9	37.8	5.08	5.15
	5.7	2.0	38.5	5.18	5.09
H-mode n°4	6.5	2.0	39.3	5.05	4.98
	6.3	2.2	40.0	4.92	4.91
	4.5	1.6	40.8	4.87	4.71
	4.8	1.9	41.6	4.67	4.65
	5.2	2.0	42.3	4.72	4.59
	5.8	1.8	43.2	4.52	4.44
	6.5	2.3	44.9	4.21	4.30
	4.7	1.9	45.0	4.40	4.23
	5.2	2.0	46.1	4.29	4.13
	4.6	1.9	46.7	4.33	4.04
	5.3	2.1	47.6	4.17	3.97
	5.5	2.0	49.2	4.07	3.77
	5.3	1.9	49.6	3.96	3.73
	4.4	2.4	50.4	4.09	3.70
	4.0	1.9	50.8	3.93	3.61
	5.5	2.3	52.9	3.70	3.44
	4.8	2.4	53.7	3.80	3.37
	5.2	2.2	54.6	3.58	3.26
	2.5	5.1	34.9	5.71	6.17
	1.7	3.4	34.9	5.86	5.85
	3.5	2.2	34.9	5.53	5.63
	2.0	0.2	34.9	5.40	5.28
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	1.8	-8.0	34.9	4.39	4.00
	1.6	-9.2	34.9	4.29	3.83
	1.5	-10.4	34.9	4.13	3.67
H-mode n°5	1.5	-11.2	34.9	3.98	3.57
	1.2	-12.4	50.2	2.58	2.40
	2.4	-10.7	50.2	2.70	2.51
	2.4	-9.0	50.2	2.94	2.63
	2.1	-7.9	50.2	3.05	2.72
	3.8	-4.4	50.2	3.27	3.02
	2.6	-2.5	50.2	3.54	3.20
	4.0	-1.7	50.2	3.52	3.28
	5.4	0.0	50.2	3.57	3.45
	4.6	1.1	50.2	3.79	3.57
	3.0	1.5	55.0	3.47	3.16
	2.4	2.0	55.0	3.56	3.21

Test	superheat (°C)	T _{EV} (°C) (dew point)	T _{CD} (°C) (dew point)	COP _{exp}	COP _{mod}
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	3.8	7.8	47.9	3.79	3.71
	3.8	7.1	49.1	3.44	3.45
	3.8	6.5	51.1	3.22	3.13
	3.2	6.4	52.7	3.02	2.93
	3.9	5.4	53.1	2.92	2.78
	3.6	4.8	54.3	2.80	2.58
	3.8	4.3	55.4	2.60	2.43
	3.9	4.0	56.3	2.52	2.32
	4.0	3.6	57.5	2.35	2.17
	4.2	3.1	58.1	2.29	2.08
C-mode n°1	4.2	2.6	58.3	2.29	2.02
	4.2	2.4	58.7	2.17	1.97
	4.0	2.1	58.8	2.12	1.94
	4.9	1.9	59.7	2.08	1.86
	4.2	1.7	59.8	2.03	1.83
	4.1	1.3	60.1	2.03	1.78
	4.1	0.9	59.7	2.00	1.78
	4.1	0.6	60.0	1.88	1.73
	4.3	0.1	59.4	1.91	1.74
	4.3	-0.2	60.1	1.88	1.67
	4.1	-0.4	59.7	1.81	1.68
	4.3	-0.8	59.9	1.79	1.63
	1.6	2.5	44.7	3.56	3.34
	2.6	1.0	45.4	3.40	3.07
	3.0	0.6	45.8	3.25	2.98
C-mode n°2	2.7	-0.2	46.0	3.24	2.85
	2.8	-0.7	46.1	3.16	2.78
	3.0	-1.0	47.0	3.03	2.66
	3.0	-1.4	46.8	2.97	2.63
	2.9	-1.7	46.8	3.00	2.60

Test	superheat (°C)	T _{EV} (°C) (dew point)	T _{CD} (°C) (dew point)	COP _{exp}	COP _{mod}
S-mode n°1	3.0	0.9	31.4	10.63	10.88
	3.7	0.3	31.3	10.77	10.66
	5.6	0.0	32.8	10.13	10.12
	5.2	-0.8	31.7	9.91	10.14
	5.9	-1.2	31.5	9.84	10.07
	4.5	-1.7	31.5	9.91	9.88
S-mode n°2	3.9	6.7	41.1	10.20	10.00
	3.0	5.7	41.3	9.99	9.61
	4.3	5.4	41.4	9.41	9.48
	3.5	4.5	42.3	9.29	8.91
	4.3	3.9	44.2	8.65	8.21
	4.4	3.3	45.5	8.31	7.73
	4.8	2.9	47.3	7.75	7.22
	4.6	2.5	47.8	7.63	6.99
	4.7	2.0	49.4	7.21	6.54
	4.6	1.6	49.9	6.91	6.34
	4.9	1.2	50.2	6.80	6.17
	4.6	0.8	51.4	6.47	5.86
	4.9	0.5	53.4	6.07	5.44
	4.9	0.1	53.8	5.91	5.29
	4.3	-0.3	55.3	5.74	4.97
4.7	-0.5	55.8	5.61	4.86	
S-mode n°3	3.5	5.9	41.5	9.77	9.61
	7.1	3.8	41.5	8.81	8.91
	3.4	6.0	43.1	9.59	9.19
	5.1	2.8	43.1	8.81	8.18
	3.0	3.5	43.5	9.09	8.30
	4.3	2.7	45.1	8.32	7.67
	5.0	2.6	45.4	8.00	7.58
	5.3	2.2	47.0	7.57	7.07
	5.1	1.7	47.3	7.51	6.90
	4.9	1.3	48.3	7.18	6.58
	5.1	0.9	49.2	6.96	6.32
	5.0	0.4	50.6	6.52	5.93
	5.0	0.1	51.5	6.32	5.70
	5.1	-0.2	52.0	6.21	5.55
	5.1	-0.6	53.4	5.93	5.22
5.0	-0.9	54.6	5.74	4.99	
5.5	-1.2	55.3	5.48	4.82	
S-mode n°4	2.8	6.6	49.9	7.50	7.55
	1.5	4.5	49.4	7.86	7.14
	2.2	2.7	50.3	7.27	6.50
	3.9	2.3	49.9	7.20	6.48
	4.4	1.9	50.0	7.04	6.39
	3.5	1.7	50.2	7.06	6.28
	3.7	1.4	50.5	6.78	6.15
	3.9	1.1	50.8	6.75	6.04
	4.0	0.8	51.8	6.44	5.79
	4.2	0.6	51.7	6.45	5.78
	4.8	0.3	52.4	6.27	5.58
	3.8	0.1	53.1	6.19	5.42
	4.3	0.1	52.9	6.22	5.45
	3.7	-0.2	53.0	6.11	5.37
	3.3	-0.4	52.8	6.20	5.37
3.5	-0.5	53.9	5.98	5.17	
3.7	-0.7	54.0	5.90	5.12	
S-mode n°5	1.2	4.0	35.5	10.95	10.73
	2.3	2.0	35.5	10.43	10.04
	2.6	1.8	35.5	10.24	9.95
	3.7	1.1	35.5	9.99	9.70
	3.7	0.3	35.5	9.77	9.43
	3.6	-0.3	35.5	9.69	9.24
	3.9	-0.7	35.5	9.47	9.09
	3.7	-1.3	35.5	9.34	8.91