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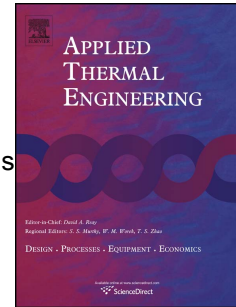
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An innovative system for feeding once-through evaporators in flooded conditions

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Abstract

In this paper an innovative feeding system for once-through flooded evaporators is presented and experimentally analysed.

The mentioned system consists of an electronically operated expansion valve and a small liquid separator placed at the evaporator exit, equipped with a level indicator. The basic idea is to get the control signal for the expansion device from the liquid level in the separator. An additional internal heat exchanger must follow the evaporator to prevent any liquid from flowing back to the compressor.

The proposed solution retains the benefits of flooded evaporation, without the need of liquid recirculation, thus keeping the simplicity and flexibility of the systems equipped with thermostatic valves. It is suitable both for single evaporator and multi-evaporators lay-out.

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To verify the potentialities of the proposed solution, a simple algorithm has been developed to control the valve.

The first experimental results have shown the ability of the system to keep stable operations of the evaporator under flooded conditions. The comparison with a dry-expansion circuit has shown large potential of energy saving.

Keywords: Thermostatic expansion valve, Flooded evaporator, Dry expansion evaporator, Superheat, Level indicator.

1. Introduction

Within the scope of improving energy efficiency in vapour compression cycles, the optimisation of each component of the circuit acquires great value.

Evaporators may become a source of inefficiency whenever their heat transfer area is not properly used. In the case of single-phase vapour flow, the limited flow heat capacity of the vapour penalises heat transfer. Moreover, single phase vapour flow involves low heat transfer coefficient, refrigerant side; if the related thermal resistance approaches the one on the secondary fluid side, or lowers under this value, overall heat transfer coefficient can be severely penalised.

When using a thermostatic expansion valve, either mechanical (TEV) or electronically controlled (EEV), as the throttling device, the refrigerant flow is controlled so that a pre-set superheat value is maintained at the evaporator exit with limited deviations. As a consequence, part of the evaporator is interested by single-phase vapour flow, which results in a loss of heat transfer capability.

Despite the above mentioned limitations, thermostatic expansion valves are the most utilised throttling devices, as they are easily installed and managed, mainly because they operate with once-through evaporator, thus avoiding refrigerant recirculation, that is generally needed in traditional flooded evaporators. The refrigeration system is indeed very flexible as each evaporator is individually controlled and ideally no liquid is coming out of evaporators, so that compressors can safely work. Unfortunately, attempts to reduce the superheat value, in order to improve the evaporator efficiency, face the so-called hunting problem. Hunting is defined by the ASHRAE [1] as "a condition that occurs when a controller [...] continuously overrides and undershoots or overshoots the control point, with resulting fluctuation and loss of control of the condition to be maintained", i.e. the TEV fails in controlling the superheat and the temperature at the evaporator exit fluctuates too much.

First of all, instability derives [2] from the stochastic nature of two-phase flow, which determines, for example, random variations in the extension of the two-phase region, thermal non-equilibrium at the evaporator exit and vapour bubbles, causing pressure fluctuations through the evaporator [3]. In addition, some other factors might enhance the instability, such as the different response time of the two basic variables that control the action of the expansion valve itself, namely the pressure signal (at the evaporator inlet or outlet), which is immediately detected, and the superheat signal, which involves a significant time lag.

Literature studies have yielded two possible explanations for the hunting behaviour of the TEV evaporation system: some authors think it is caused by the evaporator characteristics ([4], [5], [6], [7], [8]): in particular Wedekind and Stoeker [4] experiment the oscillatory nature of the mixture-vapour transition

point and relate it to physical parameters that include fluid properties, cross sectional area of the tube, heat flux and void fraction; Huelle [7], [8] explicitly states that a dry evaporator cannot be operated at a lower superheat than the minimum stable one without hunting, therefore it is the evaporator and not the valve that determines the least possible superheat.

Other Authors believe that hunting is the reflection of a stability problem of the control system of the throttling valve ([9], [10], [11]), while Higuchi [12] relates it both to evaporator and TEV characteristics.

Yasuda [13] discusses the effects of PI parameters on the stability of the system, and proves that increasing the values of the constants handling the proportional and integral actions of a PI controller will lead to hunting even in presence of an EEV. Chen et al. [14] demonstrate that for an EEV-evaporator system, the minimum stable superheat exists and has the same importance as in the TEV system; these authors suggest that the variation of flow regime and heat transfer coefficient is primarily the reason for minimum stable superheat, and this phenomenon is not just due to control problems.

In a recent work, Fallahsohi et al. [15] apply a Predictive Functional Controller (PFC) to control the evaporator superheat: they demonstrate that it can reduce and better control the superheat than a PID controller; they also measure the improvement in COP, which in the specific situation reaches 5.9%.

In the case of high superheat, the probability that the stochastic variations of two-phase flow reach the evaporator outlet is reduced; this is the reason why sometimes users are forced to set the expansion valve for operating conditions that penalise the thermal efficiency (high superheat).

The superheat value can't be practically set below 5K, otherwise instability problems in superheat control might arise.

On the other hand, multi-circuit dry expansions evaporators often suffer from another source of inefficiency, related to non-uniform flow distribution among the different circuits or unbalanced air flow on the face area of the coil. The superheat value imposed by the thermostatic expansion valve in general is a consequence of the mixing of few streams of humid vapour with many streams of largely superheated vapour and the global effect can be severe penalisation of the heat transfer capability. Often in such circumstances the liquid fraction exiting from some circuits promotes instability in the operation of the system, connected to the already mentioned stochastic variations of two-phase flow. Of course, flooded operation of the evaporator could remove any problem of this kind.

Aganda et al. [16] analyse the evaporator for a packaged air conditioning unit controlled by a TEV; in their specific situation, in the case of airflow maldistribution, they estimate that the penalisation in the evaporator performance related to the TEV action can achieve 38%. Below-zero operations of the multi circuits evaporators with uneven air flow enhance the efficiency penalisation due to uneven frost distribution: Huang et al. [17] investigate the phenomenon of hunting in a multicircuit evaporator controlled by a TEV during the frosting period.

The limitations and the drawbacks of the traditional TEV evaporator control can be overcome in single once-through evaporator systems according different proposal, but none of them up to now was successful and came into general use. Typical solutions found in the open literature consist in controlling the liquid level on the high pressure side of the plant [18], in controlling the subcooling ([19]; [20]) or in controlling the high pressure as it is common practice in transcritical cycles [18]. In all the mentioned solutions, the refrigerant mass flow

to the evaporator is not directly controlled as a function of the outlet conditions, but the system is charged so that a certain amount of liquid leaves the evaporator; an internal heat exchanger (IHX) between the liquid line and the suction line is then needed to evaporate the liquid excess. The main drawback of such techniques is the practical impossibility of being used in multi-evaporator systems, mainly because the problem of evenly distributing two-phase flow amongst several evaporators.

As far as the authors are aware, only a patent was published dealing with a multi-evaporator transcritical system, where high pressure is controlled and once-through evaporators are overfed as described above [22]; however there are no evidences that this system was successfully tested and came into operation so far.

Another way for promoting flooded operation of once-through evaporators consists in warming up the TEV temperature sensor using an electric resistance or other means, so that the perceived superheat results from the thermal balance between the heating power and the cooling power from the two-phase flow on the refrigerant side; it is of course necessary to include an additional heat exchanger to prevent the liquid leaving the evaporator from reaching the compressor. This method has been proposed, for example, by Granryd [23]; many authors have tried to find a method for evaluating the liquid fraction out of the evaporator when heating up the TEV sensor; amongst the others, we quote patent GB2219661 [24].

Similar results may be obtained by placing the TEV sensor after the IHX, as described, for example, in the US Patent 6460358B1 [25]: the superheat takes place inside the IHX where high temperature difference is present between the two side of the heat exchanger, thus assuring complete flooding in the

evaporator. Unfortunately this arrangement will create a well known control problem, resulting in unstable evaporator operations, because of an initial feedback action contrary to the steady-state dependence of superheat on the mass flow rate. This problem is hard to be solved with traditional control techniques. Either specific very advanced control logics, in the case of EEV, or physical devices that can stabilise the sensor signal, such as an increase in the thermal mass of the TEV sensor, have been so far proposed to solve the problem. It is also known since long time that a fixed orifice in parallel with the thermostatic valve can lead to stable operations; Malm [26] experimentally verifies this statement.

Finally, in the case of multi-circuit evaporators with unbalanced circuits, Forsmand [27] proposes to place the TEV bulb in an underfed circuit, so that this circuit is no longer penalised, but other circuits may be overfed; an internal heat exchanger between the suction line and the liquid line (IHX) must be included for the safety of the compressor. This solution requires a dedicated investigation on each evaporator to find out the underfed circuit where to place the bulb.

In this paper an innovative feeding system for once-through flooded evaporators will be presented and analysed. The basic idea is to get a control signal for the expansion device from a liquid level sensor at the exit of the evaporator. The proposed system assures both flooded operation of once-through evaporators and good stability of the operational variables so enabling the use of simple and reliable control logics.

The first experimental results have shown the ability of the system to keep stable operations of the evaporator under general operating conditions.

2. The concept of the innovative system

The aim of this paper is to present and investigate an innovative system, which enables once-through evaporators to operate in flooding conditions, that is with some liquid fraction at the exit.

The basic idea is to overfeed an evaporator so that a certain amount of liquid is continuously exiting from it; an internal heat exchanger between the suction line and the liquid line (IHX) must be included to evaporate the liquid excess coming out of the evaporator. The vapour quality needs to be controlled so that the evaporator never be starved and the liquid fraction never be higher than the amount that can evaporate inside the IHX; of course, in all circumstances, stable operating conditions must be assured.

The concept is quite similar to those presented, amongst the others, by Granryd [23] and Shannon et al [28], except for the specific control signal which is chosen.

The design of the innovative system, described in the following, was patented [29], and it was given the commercial name VQM[®] (Vapour Quality Management), which will be used in this paper for the sake of simplicity.

Figure 1 illustrates the lay-out of the system. The basic idea is to have a small vessel (3) at the exit of the evaporator (1), where liquid and vapour can be separated. Under steady-state conditions of the whole system, if the separator vessel is adiabatic, when a certain amount of liquid is continuously drained from it and the liquid level is constant, the vapour quality at the evaporator exit is given by the ratio of the mass flow rate of the drained liquid to the total mass flow rate exiting from the evaporator.

Within this concept, the refrigerant flow into the evaporator (1) needs to be controlled so that the liquid level in the separator (3) be constant. The electronic expansion valve (2), which manages the refrigerant flow, is controlled by a liquid level (4) signal in a feed-back loop. An optical sensor has been chosen as liquid level sensor.

The mass flow rate of the drained liquid depends on the pipe system design, which determines the pressure head available between the separator vessel and the vapour line at the insertion point of the drainage line. As a consequence, the pressure drop in the vapour line determines the pressure head for the liquid drainage; thence, if the pressure drop, both for vapour and liquid flow, can be assumed as proportional to the square power of the respective mass flow rates, the ratio of the liquid to the vapour flow, and therefore the vapour quality at the evaporator exit, does not depend on refrigerant flow, but is determined only by the design of the system.

The internal heat exchanger IHX (5) evaporates the liquid fraction leaving the evaporator and at the same time subcools the liquid directed to the expansion valve.

3. Experimental set-up

The VQM[®] device which was tested consists of a liquid separator (3), equipped with an optical liquid level sensor (4), an internal heat exchanger (5) and an electronic expansion valve (2), which are arranged as represented in Figure 2. The evaporator (1) is a finned coil heat exchanger.

The liquid separator (3), equipped with the level sensor (4), is represented in details in Figure 3: vapour and liquid coming from the evaporator enter the separator; liquid is collected at the bottom due to gravity force. Vapour flows

through the pipe heading to the internal heat exchanger. The calibrated hole (A), through which the liquid is removed from the separator, is located slightly underneath the fixed level of the vapour-liquid interface so that the gravity head be minimised compared with the pressure head as the driving force of the liquid flow; the purpose is keeping nearly constant the liquid fraction exiting from the evaporator as the mass flow rate of refrigerant varies.

The liquid level sensor (4) is an optical device (Figure 4), which is able to discriminate whether its apex is wetted by liquid or by vapour and operates on the different refraction indexes; the liquid level is detected with a precision of $\pm 2 \cdot 10^{-3}$ m. The output signal from the liquid level indicator is a digital on/off signal.

The internal heat exchanger (5) is a tube-in-tube heat exchanger; it was sized so that liquid is completely evaporated and only superheated vapour can reach the compressor. However, for safety reasons, the experimental setup includes a suction liquid receiver (6), which protects the compressor in the case of liquid flow back.

The expansion valve (2) uses a pulse width modulation technique (PWM): applying the PWM signal as the control input to a switching valve makes the valve on and off successively. By switching between these two states, and by varying the duty ratio of the on time, the mean refrigerant flow can be modulated.

The test rig was equipped with a semi-hermetic reciprocating compressor (7). The condenser (8) is a finned coil heat exchanger, followed by a liquid receiver (9), thus assuring saturated liquid at the condenser exit and acting as a compensating volume to receive refrigerant, when expelled from the main components of the refrigerating circuit, or to supply refrigerant when needed.

The refrigerant is R134a.

The main characteristics of the tested VQM[®] and of the test rig are summarised in table 1.

After some tests of the system, manually operated to verify its general behaviour, a simple algorithm was specifically developed to control the valve. The basic concept consists in using a sort of integral action based on the liquid level; the valve opens when the level is above the set point and close if the level is below. The sensor signal output was used to set the PWM duty cycle: the fraction of time when the valve is on/off is proportional to the time of vapour/liquid sensor active state.

The circuit was equipped with temperature and pressure sensors located as shown in Figure 2. In addition, the evaporator was monitored with 10 temperature sensors, located on some tube bends. Temperature and pressure measurements were acquired with an Agilent 34970A data logger equipped with two 34901A-20-channel modules.

Copper-constantan thermocouples (T type) were used as temperature sensors. They were fixed on tubes and bends and thermally isolated from external ambient. The estimated accuracy of the entire temperature measurement system is ± 1.5 °C.

Suction pressure was measured at the suction of the compressor. A pressure sensor (Druck Incorporated PMP 4070) with 0-10 bar measuring range was used. The accuracy of the pressure transducer is $\pm 0.1\%$ FS.

5. Experimental results

The first set of tests was aimed at figuring out the ability of VQM[®] of steadily maintaining evaporator overfeeding.

The system was placed in open air, in an uncontrolled environment; it was run until it reached stable operations.

At 21 °C ambient air, Figure 5 shows the evaporator temperature measured on tube bends, which attest saturation conditions, without any deviation along the evaporator surface temperature due to superheat. On the other hand, the suction temperature was high enough to assure safe compressor operations. In the same figure, the liquid level indicator signal is represented on the right axis.

When operating at about 19°C ambient temperature, one of the evaporator fans was switched off, to evaluate the reaction of the controller to a sudden change in thermal load. Figure 6 shows the evaporator bend temperature recorded during the test, as well as, on the right axis, the level signal: the saturation temperature was maintained throughout the test.

Finally, the evaporator was partially closed inside an insulated box, to reduce the thermal load, and a comparison test between the VQM[®] system and a thermostatic expansion valve was performed, simply opening the ball valve (11) to enable valve (10) to operate, while valve (2) was kept close. Figure 7 shows that VQM[®] allowed a better performance, in terms of refrigerating capacity, with much higher evaporator temperature, due to the absence of the superheated area which heavily penalises dry expansion evaporators.

6. Conclusions and future developments

The experimentation demonstrated that VQM[®] assures total wetting of the heat transfer surface, with significant impact on the overall heat exchanger performance. In addition, the system can easily replace the thermostatic valve,

as satisfactorily operates on once-through evaporators, without any need for recirculation. When compared with traditional flooded systems, the final installation results much simpler and the overall refrigerant charge would be much lower, thus providing a great benefit when toxic or flammable refrigerants are used.

When compared with a dry-expansion system, the energy saving that can be achieved with the suppression of the superheating region depends very much on the performance of the original system; the larger is the dry region of the evaporator, the higher is the energy saving when flooding the evaporator; large superheat area occurs when the evaporator operates under low temperature difference between refrigerant and air and high superheat value.

As all the heat transfer area is effective, VQM[®] allows the reduction of the temperature difference between the evaporating refrigerant and the air, so that in refrigerated storage the weight loss, that affects sensitive products, such as vegetables or unwrapped meat, is reduced; this is a consequence of higher temperature surface in the air cooler, which in its turn reduces dehumidification.

The absence of vapour superheat can be beneficial also under partial load, when the temperature difference between refrigerant and air can be reduced almost proportionally to the reduction of the cooling load, as no minimum difference is necessary to assure the required superheat.

Finally, once-through flooded evaporators can help in solving the well known problem of uneven refrigerant distribution, or unbalanced thermal loads, in multi-circuit evaporators: if some liquid fraction is present at the evaporator exit, it could be possible to slightly overfeed also those circuits that in traditional dry expansion evaporators are underfed, so severely penalising the overall performance of the heat exchanger.

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FIGURES

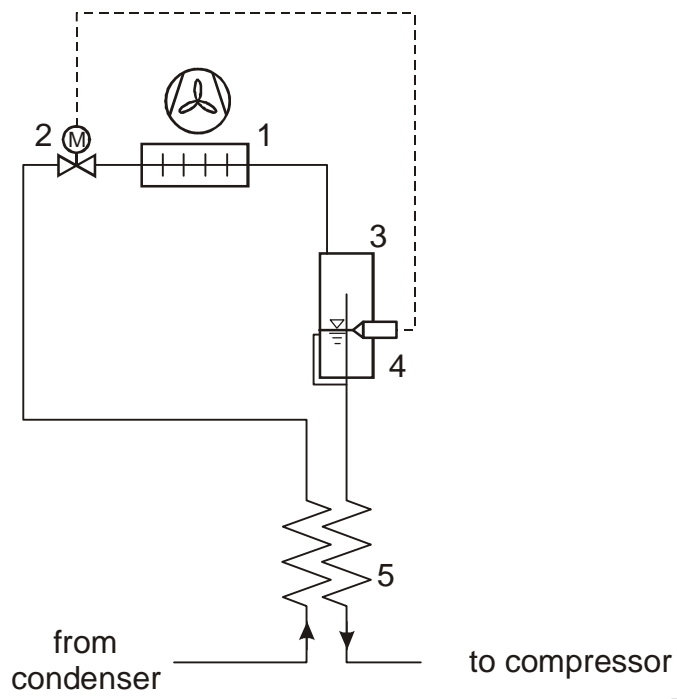


Fig. 1

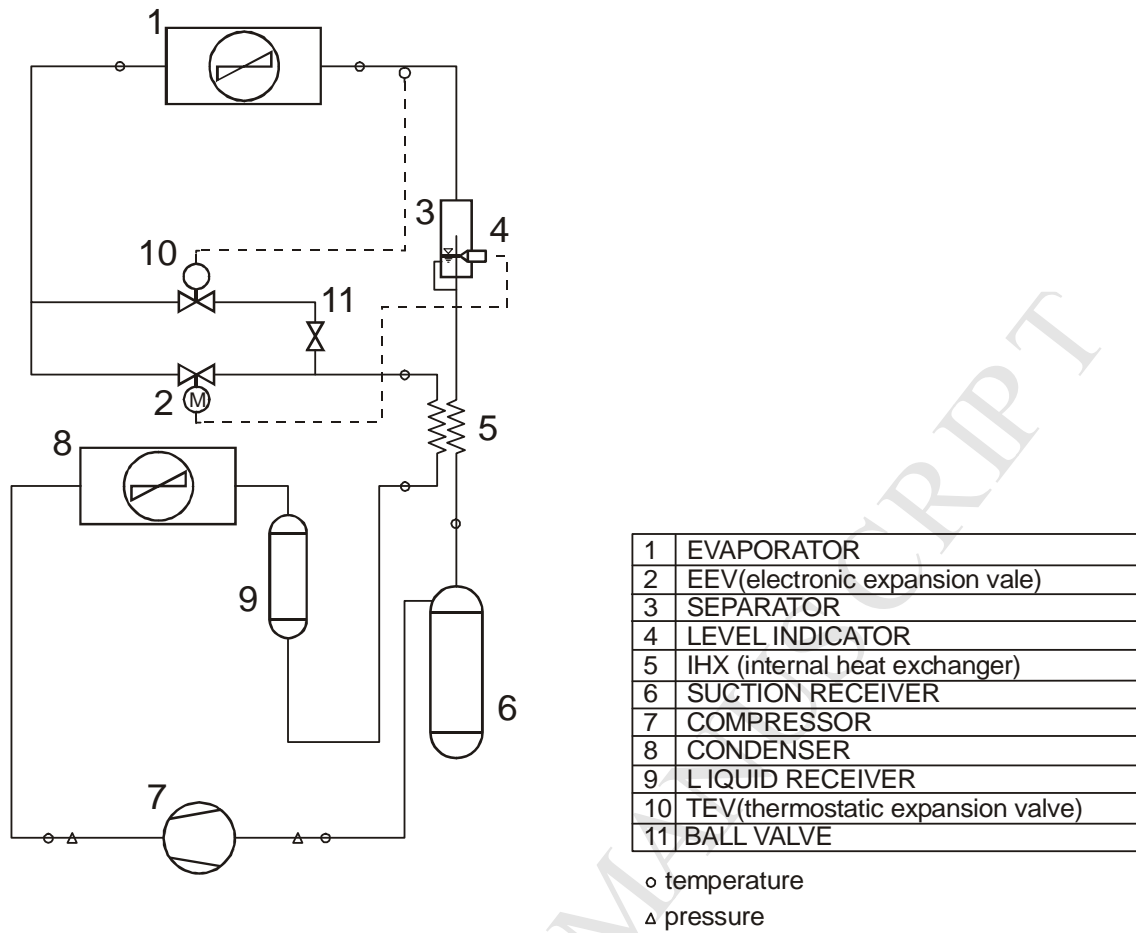


Fig. 2

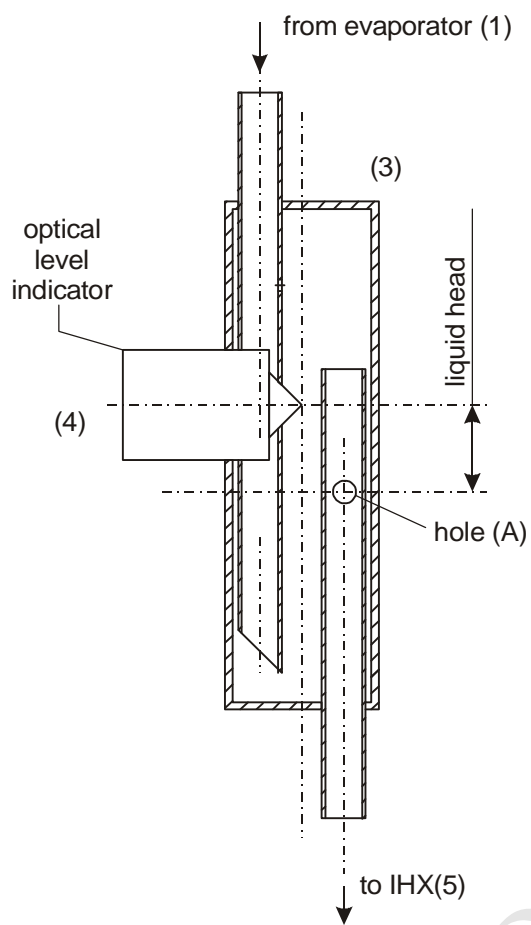


Fig. 3



Fig. 4

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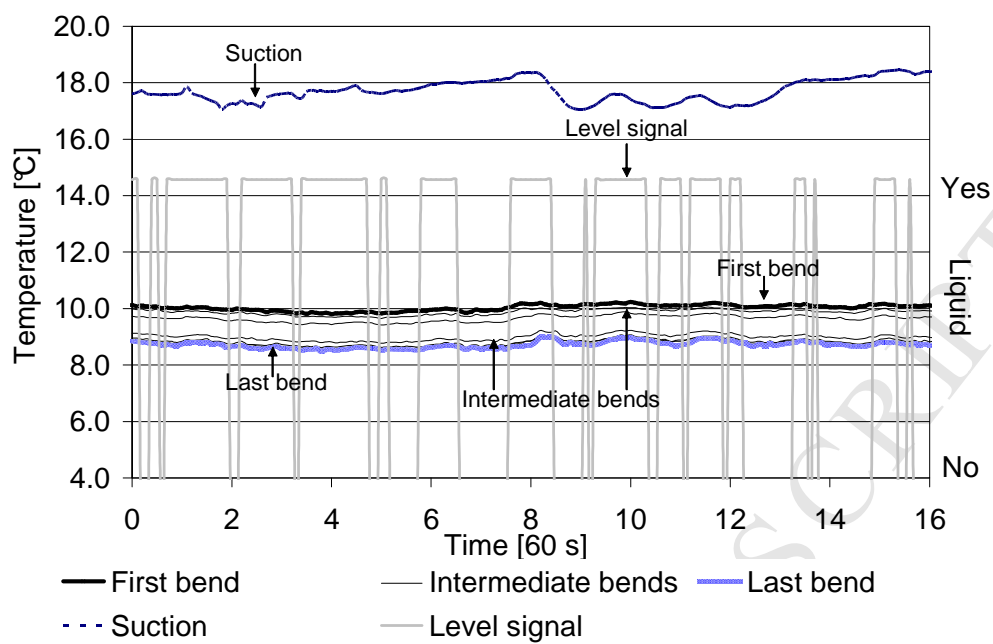


Fig. 5

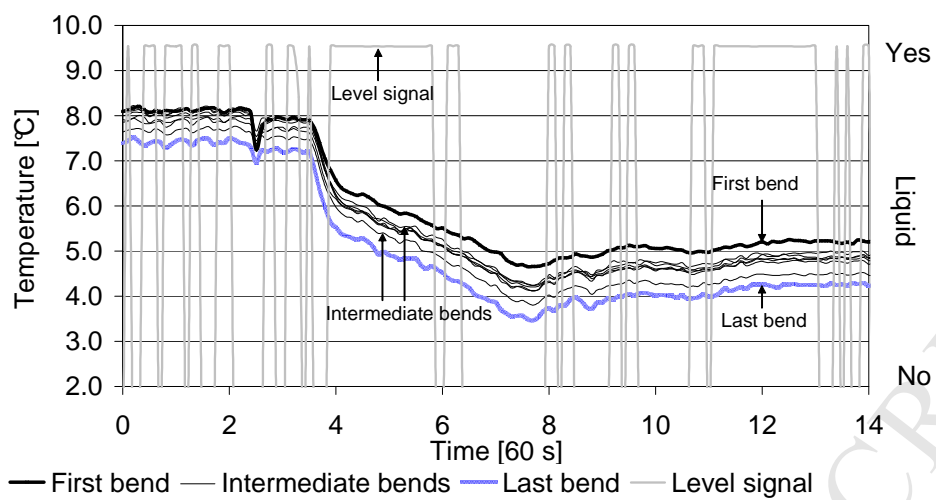


Fig. 6

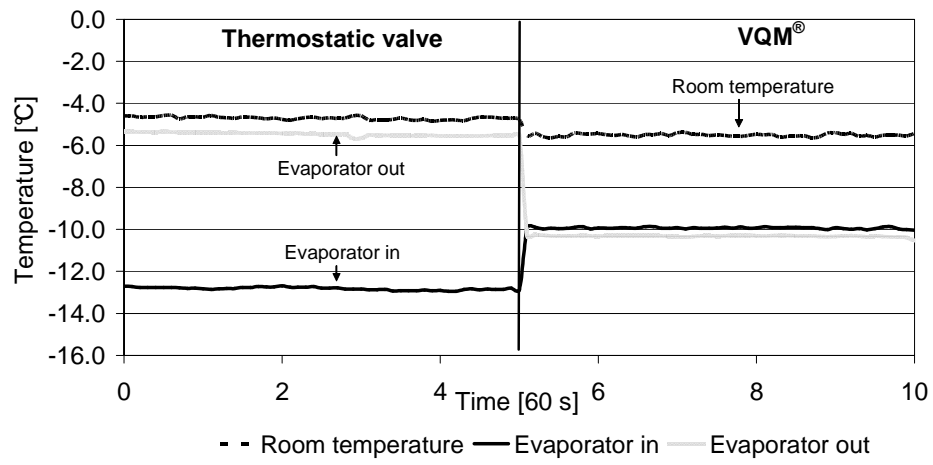


Fig. 7

FIGURES CAPTIONS

Fig. 1. VQM[®] systems:

Fig. 2. Test rig lay-out

Fig. 3. Liquid separator equipped with level indicator

Fig.4. Level optical sensor

Fig.5. Evaporator bend temperature, suction temperature and liquid level signal during steady-state operations.

Fig.6. Evaporator bend temperature and liquid level signal during transient operations due to thermal load reduction.

Fig.7. Comparison test between VQM[®] and thermostatic expansion valve: evaporator inlet and outlet temperature and room temperature.

TABLES

Table 1.

	Figure 2	Description
Evaporator	(1)	Finned coil. External Area 25.82 m ² . Internal Area 0.57m ² . Front air velocity 1 m s ⁻¹
Electronic expansion valve	(2)	PWM valve. Flow area 2.27*10 ⁻⁶ m ²
Liquid Separator	(3)	Gravity liquid separator. Internal volume 1.79*10 ⁻⁴ m ³
Liquid level indicator	(4)	Optical sensor
Internal heat exchanger	(5)	Tube-in-tube. Heat transfer area (low pressure side) 0.075 m ²
Low pressure receiver	(6)	Internal Volume 13 10 ⁻³ m ³
Compressor	(7)	Semi-hermetic, reciprocating. Swept volume (50Hz): 2.89 m ³ h ⁻¹
Condenser	(8)	Finned coil. External Area 27.32 m ² . Internal Area 1.25m ² . Front air velocity 1.5 ms ⁻¹
Liquid receiver	(9)	Internal Volume 7*10 ⁻³ m ³
Thermostatic valve	(10)	
Ball valve	(11)	