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An experimental investigation of performance characteristics of an energy-efficient air conditioning in vehicle

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Abstract. In order to reduce the fuel consumption of air-conditioning in vehicle, an air conditioning system was designed based on the principle of direct evaporative cooling and liquid dehumidification. In this paper, main devices were conducted in the way of numerical simulation and experiment, the overall layout of the device was designed under the guidance of Solidworks. The results showed that the high temperature and humidity air could be changed into the livable air. In particular, the regenerator could be operated with waste heat from the engine for higher energy efficiency. It can achieve the effect of the temperature dropped by 5-7°C which need less energy than the traditional car air-conditioning while satisfy the comfort of the human body.

1. Introduction

Vehicle are usually equipped with air conditioning systems to provide comfortable cab environment for driver. The air conditioning system is expected to reduce temperature and dehumidify of air in the cab condition, both functions require the mechanical power delivered by the internal combustion engine [1]. Air conditioning need higher quality because of the wicked environment including sunlight exposure, densely populated, velocity variation [2]. At this stage, air conditioning in truck is composed of compressor, condenser, throttle element, evaporator, blower and the necessary control components [3]. The thermal efficiency of internal combustion engine is about 30% to 40%, of which less than half of the energy for the power output, 25% of the energy is lost in the form of cooling water, 10% of the fuel is used in the car air conditioning system [4].

In open loop air conditioning system, the refrigerant used for refrigeration must be non-toxic and harmless [5]. As a natural working substance, water is cheap, accessible and environmentally friendly. In addition, there is no compressor in this new equipment, that is, there is no rotating parts, which reduces noise energy consumption.

In recent years, people pay more attention to the research of membrane dehumidifier and dehumidifying technology which based on the penetrative and selective performances of membrane, in the whole process, there is always a partial pressure difference of water vapor between both sides of the membrane forming a continuous process [6].

The air-conditioning system of vehicle is facing energy consumption problems. It is necessary to reduce the fuel consumption of air conditioning while making driver's working environment well. The research is of great significance to develop an energy-saving, environmentally friendly and economical air-conditioning system.

2. Experiment section

2.1. Feedstock materials

Polylactic acid(PLA) was used for most part of the device, acrylic(PMMA) were used as the feedstock for parts to be subjected to high temperatures. Water was the refrigerant in this air conditioning, lithium bromide solution with a concentration of 50% was used as liquid dehumidifier. Polyvinylidene fluoride(PVDF) membrane was used in dehumidifier.

2.2. Machine layout and workflow

The air conditioning system was consisted of four main units: the ejecting humidification device, two dehumidifiers and the regeneration of lithium bromide solution device. The theory of this air conditioning system was shown in figure 1. The whole circulation could be divided into the gas circulation and the liquid circulation. The high temperature and humidity air A1 was blown into the primary dehumidifier 5 under the action of the blower 1, while the wet air passed through the air flow path in the primary dehumidifier 5, water was absorbed by the lithium bromide solution through the PVDF membrane. High temperature and low humidity air A2 was gained. The ultrasonic atomization device 3 constantly atomized the water in the reservoir 4 into a mist, Negative pressure is formed at the nozzle of the ejector 2 while the air A2 entered, which could inhale the mist into the ejector 2. The water mist evaporated in the ejector 2 also absorbed heat. The low temperature and humidity air A3 was obtained and discharged from the nozzle outlet of the ejector 2. Air A3 need to be dehumidified through the secondary dehumidifier 6 for an appropriate temperature and humidity.

The lithium bromide solution was pumped from the reservoir 8 through the pumps 7 and 12 into the dehumidifier, it would be circulated back to the reservoir 8 after dehumidification. A density detection which monitored the height difference between the float and the liquid level at different concentrations based on the relationship between the concentration and the buoyancy was placed in the reservoir 8. Liquid circulation began when the solution concentration was below 40%, low concentration solution was inhaled into regenerate device 9, pump 10 pumped the solution to the cooling tank 11 while finished regeneration. The solution would be pumped into the reservoir 8 after cooling down.

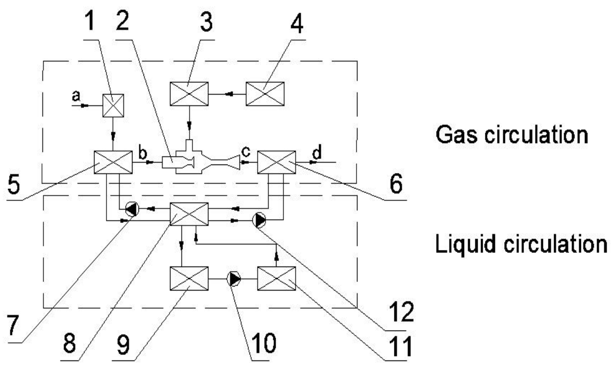

Figure 1. The theory and entity graph of the air conditioning system. (1) blower; (2) ejector; (3) ultrasonic atomization device; (4) water storage device; (5) primary dryer ;(6) secondary dryer; (7) Pump; (8) Solution storage device; (9) regeneration device; (10) pump; (11) Cooling pool; (12).

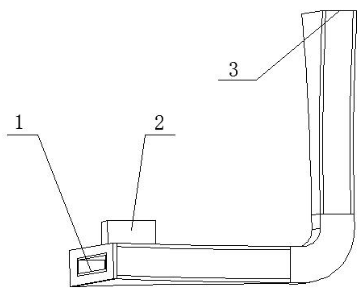

Figure 2. Model of ejector. (1) Eject inlet; (2) Ejected inlet; (3) Air outlet.

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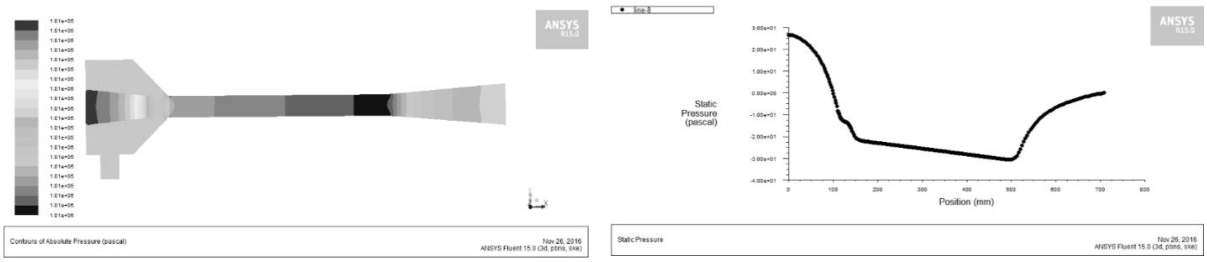
2.3. *Ejecting humidification process*

The ejecting humidification is shown in figure 2. The direct evaporative refrigeration process in ejector was the core of the circulation. The injection process of ejector was simulated by Fluent. Figure 3 shows the internal pressure and flow velocity while the air inlet velocity of the ejector was 3m/s. It can be seen that the water mist produced by the ultrasonic atomizer was inhaled into the ejector under the action of negative pressure.



(a) Pressure distribution in ejector (b) Pressure distribution on the central axis of ejector

Figure 3. Internal pressure and flow velocity of ejector.

2.4. *The dehumidfifier*

The primary dehumidifier is shown in figure 4. PVDF membrane was supported by several columns. lithium bromide solution was pumped into three spray tube, which had certain quantity of holes symmetrically, the lithium bromide solution flowed out from the holes and sprayed onto the PVDF membrane. Water molecules were absorbed by lithium bromide solution through the membrane, then the solution flowed back to the reservoir.

The structure of the secondary dehumidifier is similar to that of the primary dehumidifier. The difference was that the secondary dehumidifier did not need obvious dehumidification effect.

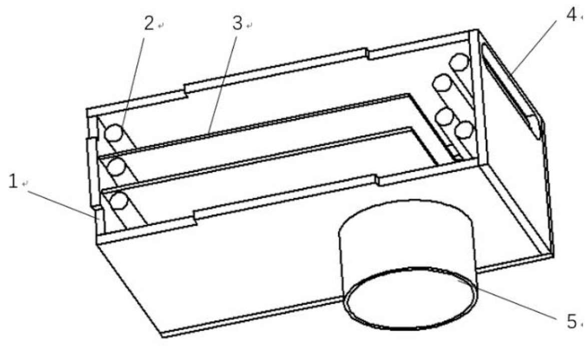


Figure 4. The model of primary dehumidifier. (1) dehumidifier housing; (2) Membrane support column; (3) Baffle; (4) Air inlet; (5) Air outlet.

Figure 5. Regeneration device of LiBr.

2.5. *Regeneration of lithium bromide solution*

The concentration of lithium bromide solution would be at a low level while working, water in the solution must be evaporated in order to ensure dehumidification effect. The escaping water was discharged by vacuum pump at the same time. The regeneration device of lithium bromide solution was shown in figure 5.

3. Result and discussion

3.1. *Machine test*

The size of the device was 600x550x400mm. The experimental device is provided as figure 6.

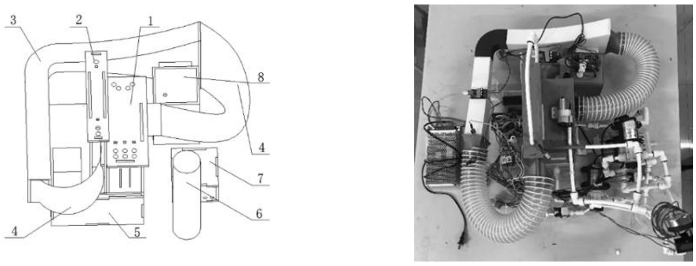


Figure 6. Test device of experiment. (1) primary dryer; (2) secondary dryer; (3) Ejector; (4) Ventilation ducts; (5) Reservoir; (6) Regeneration device; (7) Cooling pool.

The experiment was carried out under the temperature 32℃ and relative humidity 80%. When the system was stable, air conditions at the inlet and outlet were measured. An anemometer and a hand-held hygrothermograph shall be provided at the air inlet (primary dehumidifier air inlet) and the air outlet (secondary dehumidifier air outlet) to measure the outlet air flow rate, temperature and humidity.

3.2. Power consumption

The following table shows the power consumption of this device.

Table 1. Summary of power consumption equipment.

Equipment	Located	Power (W)
Blower(x2)	air inlet of Primary dryer	2
Ultrasonic atomizer	Ultrasonic atomizer device	12
Pump(x4)	Circulation of LiBr	120
Small vacuum pump	regeneration device of LiBr	1.2
Electric heating bar	regeneration device of LiBr	50

While the entire device was fully operational, the total power was 185.2W.

3.3. Evaluation criteria

Both environmental factors and the body's own factors involved in the body heat balance equation. In the multi-factor interaction, human body would have different thermal comfort, it could be evaluated through the indicators or comprehensive indicators [7]. Direct indicator referred to the environmental parameters that could be measured directly by the meters. Comprehensive indicator referred to the theoretical derivation and experimental verification, the various environmental parameters and the integration of the relevant variables obtained by the comprehensive indicators, it could more truly reflect the human body's thermal sensation.

At present, PMV (Predicted Mean Vote) indicator proposed by ISO (International Organization for Standardization) is used to describe and evaluate the thermal environment, it means the majority of people's feeling in a certain environment, which involves six parameters, the following table 2 describes the scope of these six parameters.

Table 2. Applicable Scope (ISO 7730).

Temperature (℃)	Average radiation temperature (℃)	Water vapor partial pressure (Pa)	wind velocity (m/s)	Human activity (W)	Clothing thermal resistance ($m^2 \cdot K/W$)
10~30	10~40	0~2700	0~1	46.4~232	0~0.31

The value of PMV can be calculated by the following formula.

$$PMV = \left[0.303e^{(-0.036M)} + 0.028\right]S \quad (1)$$

Which M means body energy metabolism rate, the values of M can be found in the table 3 below; S means body heat storage rate.

Table 3. Adult Men's Energy Metabolic Rate.

Activity intensity	Energy metabolism rate(W/m^2)
Lying down	46
Sitting and rest	58
Standing and rest	70
Sitting and active	70
Slightly labor	93
Heavily labor	116
Hard labor	165

The value of PMV is shown in the following table 4.

Table 4. PMV thermal sensation standard.

Thermal Sensation	Hot	Warm	Slightly warm	Moderate	Slightly cool	Cool	Cold
PMV	3	2	1	0	-1	-2	-3

PMV thermal sense scale is determined in the steady state environment, when the PMV is greater than 2 or less than -2, the result is distortion, it can be more accurately indicate thermal sensation when its value is between -2 to 2 [8].

3.4. Experimental results

The following table 5 shows the experimental results.

Table 5. The experimental data of entire device.

Serial number	Air inlet condition			Air outlet condition			COP	PMV
	Temperature (°C)	Relative humidity (%)	Wind velocity (m/s)	Temperature (°C)	Relative humidity (%)	Wind velocity (m/s)		
1	32	80	3	26.3	64.3	0.9	1.04	0.39
2	32	65	3	25.8	63.7	0.8	0.63	0.35
3	30	80	3	25.4	65.2	0.9	0.82	0.16
4	32	80	5	26.5	74.2	2.9	2.72	/

We obtained the export air state, cooling capacity, PMV value, COP value under different conditions of the initial state of the air.

$$COP = \frac{Q_t}{P} \tag{2}$$

Which

$$Q_t = m_a \Delta h \times 1000 = \rho_a v_{a,out} s_{out} \left(h_{in} - h_{out} \right) \times 1000 \tag{3}$$

Q_t —Total power of the device;

$v_{a,out}$ —Air speed of the outlet;

s_{out} —Air flow area of the outlet;

h_{in} —Enthalpy of inlet;

h_{out} —Enthalpy of outlet;

In the first three conditions, the air outlet temperature and humidity were comfortable, it could basically meet the requirements of human comfort considered from the point of view of PMV. Although the fourth working condition had a large cooling capacity and lower temperature, the relative humidity was at a high level and the wind speed reached 3m/s, which was beyond the limit which shown in the table 3. From the energy consumption point of view, the power of the entire device is 185.2W.

3.5. Uncertainty analysis of the experimental data
The uncertainty analyses of the experimental measurements are shown as follows:

(1) Temperature and humidity

The temperature and humidity of the air outlet was measured by the Rotronic HP21.

According to its measuring range and accuracy mentioned above in table 1, its uncertainty was 0.28 % and 1 %.

(2) Velocity

The velocity of air was measured by the SiWei FF-45A, its uncertainty was 5%.

4. Conclusion
During the working process, the air flow rate played a more critical role in the final air condition, and the wind speed of blower should be adjusted reasonably. The COP value of the air conditioning is about 1, which can satisfy the heat exchange of the human body surface. However, this device is better in the energy saving effect, it has a certain practical significance from point of view of fuel cost. At the air conditions including temperature 32℃, relative humidity 80%, the final air conditions of outlet can reach temperature 26.2 ℃, relative humidity 64%, it means that under the premise of reducing fuel consumption, the new type of air conditioning device can meet the comfort requirements of the human body and it has a certain application prospect in the cars.

Acknowledgments
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