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Vapor absorption refrigeration under variable environmental conditions

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ABSTRACT

In this study, the Electrolux ammonia-water-hydrogen vapor absorption system (VAS) has been analyzed for cooling load with different heat transfer media. The performance of the VAS under variable environmental conditions was investigated. It has been concluded that a high heat transfer medium is essential to have a high COP system. The cooling load of air had a COP of about 0.31%, where water improved the COP to 15%. This study also indicated that moving from natural convection to forced convection improves the evaporator temperature from -10 °C to -11.6 °C. Mist water and mist ethanol improved the evaporator temperature to -12.8 °C and -13.7 °C respectively. This study emphasizes choosing suitable heat transfer medium with the VAS maximizes the COP of the system, it also indicates that better heat transfer from the condenser such as ground source heat exchanger or pool cooling condenser must be used instead of natural convection with air.

Keywords: vapor absorption, ammonia-water, operation conditions, thermal performance, cooling enhancement.

INTRODUCTION

Refrigeration is a basic thermodynamic process, required in many engineering applications for various residential, industrial, commercial, medical, recreation purposes and many others (Hosoz & Kilicarslan, 2004). Main refrigeration systems include vapor-compression, absorption, air-standard, jet ejector, thermoelectric, and thermoacoustic refrigeration systems (Dinçer & Kanoglu, 2010). Advanced refrigeration systems such as metal hydride and magnetic refrigeration are also used for special applications (Sun et al., 2021). One of the passive refrigeration systems that can be used without electricity is the vapor absorption system (VAS) (Freeman & Markides, 2024). The VAS is used in desalination, water harvesting in addition to refrigeration. Chiranjeevi & Srinivas (2016) and Qasem et al. (2020) have analyzed the VAS for desalination purposes, best energy utilization factor or utilizing the heat from the absorber and condenser to drive the humidification and dehumidification device. This heat from the VAS was also used in heat pump system by Manu & Chandrashekar (2016). The water harvesting using VAS was investigated with metal organic framework (Xu et al., 2020). The technologies used in atmospheric water harvesting was reviewed in detail by Beithou et al. (2024), these technologies included the vapor compression, thermoelectric, absorption, COFs, MOFs and others. Kaneesamkandi et al. (2023) enhanced the condenser performance in VAS in arid areas. Such systems integrated with solar energy were all used in various applications specifically LiBr water systems (Sharma et al., 2020).

The VAS uses heat energy as driving force for the refrigeration process. Many researchers used the geothermal energy as a source of heat for the VAS (Keçeciler et al., 2000; Wang et al., 2013). The solar energy was very attractive as well, to be used in VAS as solar is available where electricity is not. Various conditions of the VAS LiBr-H_2O systems were studied, an analytical study with different solar absorption plate profiles was performed (Kundu et al., 2010). A transient parametric analysis for heating and cooling absorption system was done by Shirazi et al. (2016). Batakurki (2017) showed a brief calculation for the different stages of the VAS. Tetemke et al. (2021) analyzed the VAS driven by the geothermal energy in Ethiopia. Vapor absorption refrigeration systems (VARS) were analyzed in detail for specific working conditions. Kaynakli & Kilic (2007) performed a thermodynamic analysis of LiBr-H_2O, operating temperature and heat exchangers effectiveness on coefficient of performance (COP), load and efficiency were investigated. They found that the solution heat exchanger (SHE) has more effect than the refrigerant heat exchanger (RHE) on the parameters investigated. The startup time of a LiBr- H_2O and NH_3 systems were analyzed for different heat exchangers conditions and compared (Ebrahimnataj Tiji et al., 2020). They found that removing solution heat exchanger increases the start-up time of NH_3–H_2O by11.76% and H_2O–LiBr 45.16%. Using external energy such as solar energy for heating the generator of the system, can be used in a single effect or double effect. The influence of various operating parameters on the performance of a single or double effect systems were compared (Gomri, 2009). Optimization of the double effect LiBr-H_2O was performed (Mussati et al., 2018), they were able to reduce the annual cost by 9.5%. The energy produced in the condenser of VCS is used in cascaded system as heat input for the generator of VAS (Jain et al., 2013). Tiny heat exchangers were fabricated and experimentally tested to different absorber, condenser, generator and evaporator temperatures, good fit for high performance cooling applications was achieved (Sivalingam et al., 2021). Researchers reviewed the VAS's for different purposes, the solar powered VASs were reviewed by Siddiqui & Said (2015), experimental solar absorption cooling was reviewed as well by Aliane et al. (2016). Other researchers reviewed different techniques to enhance the energy performance (Nikbakhti et al., 2020). An updated review covers possible recent advances on absorption refrigeration systems using different working fluids and different fluids combinations with NH_3 solution were reviewed (Lima et al., 2021). The ammonia water VAS had more analyses as it is used in air conditioning and industry for its low evaporator temperature. Said et al. (2016) have reported the design, construction and operation of an NH_3-H_2O system powered with solar energy in Saudi Arabia. NH_3-H_2O system was theoretically analyzed using first and second law of thermodynamic with ejector-absorption refrigeration cycle (Habibzadeh et al., 2017). Ejector assisted vapor absorption- compression cascade system was theoretically analyzed (Jain et al., 2021). The vapor absorption system exergetic, energetic and financial were evaluated for solar driven VAS (Bellos et al., 2016). Various climatic conditions payback period of a solar absorption cooling system was analyzed in Turkey (Altun & Kilic, 2020).

The VAS efficiency, performance enhancement and optimization were targeted by researchers as well. A solar cooling system, with variable-effect LiBr-H_2O chiller and arrays of linear Fresnel solar collector has been analyzed experimentally to improve the solar cooling output and efficiency (Dai & Ma, 2017). Transient system simulation program was implemented to optimize the operation of a VAS using a solar collector integrated with a thermal storage tank (Christopher et al., 2021). Genetic algorithm was also used to optimize the double effect VARS operating conditions and were able to improve the exergetic efficiency of the system (Arshad et al., 2019). More optimization techniques such as artificial neural network was used for a hybrid absorption-recompression refrigeration system (Razmi et al., 2020).

The goal of this study was to improve the NH_3-H_2O refrigeration system performance under different environmental conditions. Air-cooled condenser, evaporative water-cooled condenser and ethanol-cooled condenser have been analyzed. Moreover, the temperature of the absorber effect on the cooling load of the VAS was also studied.

EXPERIMENTAL TEST

For evaluating the performance of VAS under variable condenser heat transfer modes. A trainer for absorption refrigeration system that consists of absorber, generator, condenser and evaporator with ammonia-water-hydrogen (Electrolux) refrigeration fluid was used. The trainer is equipped with on off power 250 V and 0.3A, sensors for voltage, current, and 4 thermocouples for the liquid heat exchanger, condenser, evaporator and absorber temperatures (Qandil et al., 2023). The device has been equipped with extra components to fulfill the data needed for analysis, such as generator temperature, condenser inlet and exit temperatures, evaporator temperatures at various distances, ambient temperature and used fluid temperature (Figure 1).

For cooling purposes, a variable speed fan has been used (Figure 2). The fan specifications included: 12 V and 1.65 A maximum power, the maximum flow rate is 64.9 cubic foot per minute which is equivalent to 1.837 m^3/min. The fan volume flow rates were divided into five sections (0.31, 0.62, 0.93, 1.24 and 1.55 m^3/min).

Prova 830 multi-input thermometer temperature recorder has been used to collect the external eight K type thermocouples (Figure 3).

METHODOLOGY

The real performance of the VAS under variable environmental conditions have been investigated theoretically and experimentally. To visualize the effect of these variables on the performance of the VAS, in an attempt to improve the coefficient of performance for the system.

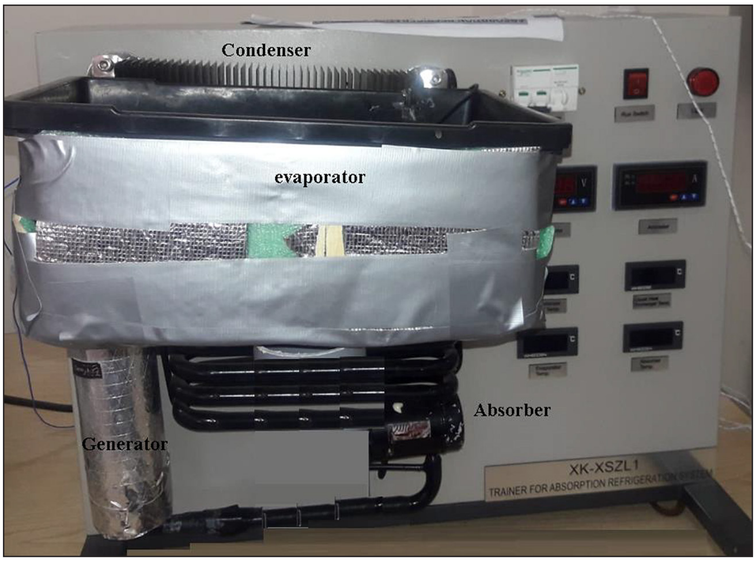

Figure 1. View of the experimental absorption refrigeration system

Figure 2. Fan cooler

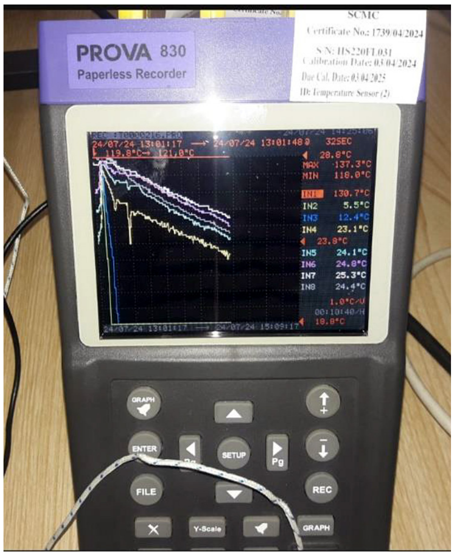

Figure 3. Prova 830 multi-input temperature recorder

Theory

Applying the first law of thermodynamics to the VAS, under steady state conditions

$$\dot{E}_{in} = \dot{E}_{out} \tag{1}$$

or

$$\dot{Q}_g + \dot{Q}_e = \dot{Q}_c + \dot{Q}_a \tag{2}$$

where: $\dot{E}_{in}$, $\dot{E}_{out}$ are energy rate entering and leaving the system;
$\dot{Q}_g$, $\dot{Q}_e$, $\dot{Q}_c$, $\dot{Q}_a$ are generator, evaporator, condenser and absorber heat transfer rates respectively.

As the ideal VAS is a reversible cycle, using the second law of thermodynamics

$$\dot{S}_g + \dot{S}_e = \dot{S}_c + \dot{S}_a \tag{3}$$

where: $\dot{S}_g$, $\dot{S}_e$, $\dot{S}_c$, $\dot{S}_a$ are the generator, evaporator, condenser and absorber entropy change rates respectively.

Thus

$$\frac{\dot{Q}_g}{T_g} + \frac{\dot{Q}_e}{T_e} = \frac{\dot{Q}_c + \dot{Q}_a}{T_c} \tag{4}$$

where: T_g, T_e, T_c – the temperatures of the generator, evaporator and condenser respectively.

As the heat transfer from the absorber and condenser is outside temperature, Dividing equation 1 by results:

$$\frac{\dot{Q}_g + \dot{Q}_e}{T_c} = \frac{\dot{Q}_g}{T_c} + \frac{\dot{Q}_e}{T_c} = \frac{\dot{Q}_c}{T_c} \tag{5}$$

or

$$\frac{\dot{Q}_g}{T_c} - \frac{\dot{Q}_g}{T_g} = \frac{\dot{Q}_e}{T_e} - \frac{\dot{Q}_e}{T_c} \tag{6}$$

Rearranging,

$$\frac{\dot{Q}_e}{\dot{Q}_g} = \frac{T_e}{T_g} * \frac{(T_g - T_c)}{(T_c - T_e)} \tag{7}$$

Which is the maximum COP of the VAS. The actual COP of the VAS is written as:

$$COP_{act} = \frac{\dot{Q}_{e,act}}{\dot{Q}_{g,act}} \tag{8}$$

Where *act* denotes to actual COP and heat transfer from generator and evaporator.

Experiments

Vapor absorption refrigeration load

To study the VAS actual behavior and performance of the VAS, the steady state performance conditions are essential. Figure 4 shows the temperature distribution versus time for the startup of the absorption refrigeration system.

The VAS takes 17 minutes to start the refrigeration effect, where the temperature of the generator is about 130 °C, and heater power of 70 W. The drop in the evaporator temperature from 29 °C to 9.5 °C within 3 minutes, and from 9.5 °C to 2.6 °C in one minute, then the temperature drops down slowly to below -5 °C. This startup behavior is taken as a reference in analyzing the effects of environmental conditions on the performance of the VAS.

The refrigeration load of the adopted system is the core of the VAS, theoretically the cooling load can be calculated from Figure 5.

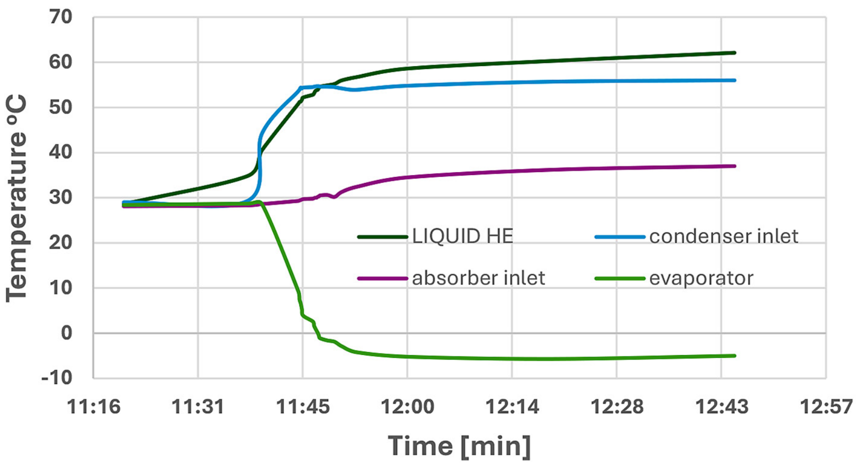

Figure 4. Temperature versus time for startup of the VAS

$$\dot{m}_{L,NH3} * h_{L,NH3} + \dot{m}_{H2} * h_{H2} + \dot{Q}_R = \dot{m}_{NH3,H2} * h_{NH3,H2}$$

or

$$\dot{m}_{L,NH3} * (h_{NH3,H2} - h_{L,NH3}) = \dot{m}_{H2} * (h_{H2} - h_{NH3,H2}) + \dot{Q}_R \quad (9)$$

where: $\dot{m}$ – the mass flow rate, h – enthalpy, $\dot{Q}_R$ – refrigeration heat transfer rate.

During the cooling process of a 6 liters air, Figure 6 is achieved. The cooling load capability of the evaporator is found from,

$$\dot{Q}_R = m_a * \rho_a * C_{p,a} * \frac{\Delta T}{t} = 0.006 * 1.2 * 1 * \frac{\Delta T}{t} = 0.0072 * \frac{\Delta T}{t} \quad (10)$$

where: ρ_a – air density, $C_{p,a}$ – air specific heat at constant pressure, t – time, ΔT – the change in temperature.

The cooling load of air by the evaporator is 0.223 W, with 70 W generator input, a COP of the cycle is about 0.31%.

The cooling load of water was reaching to 10.5 W on average, with a power supply reaching to 70 W, thus a COP of 15%. Which is a high COP for the VAS due to the high evaporator temperature (Figure 7). This can be noted from Equation (6) with higher numerator T_e and lower denominator ($T_c - T_e$).

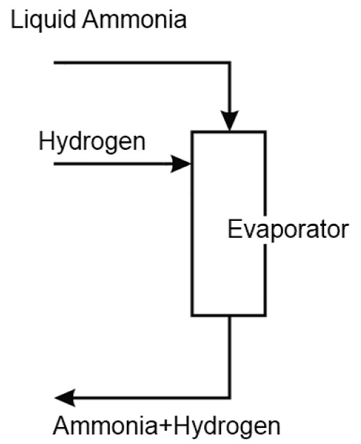

Figure 5. Schematic of evaporator

VAS with variable condenser cooling

To improve the performance of the VAS, the condenser heat transfer should be considered. Usually, the condenser exchange heat with the surrounding air, what if the heat transfer from the condenser is improved. In this section three different modes of heat transfer have been analyzed. The condenser has been subjected to a forced heat transfer by five air flow rates, mist water evaporation and mist ethanol evaporation.

Condenser air cooling

The effect of heat transfer from the condenser has been studied and compared to the steady state operations of the VAS. Five different flow rates were used (0.31, 0.62, 0.93, 1.24 and 1.55 m^3/min) (Fig. 8).

Figure 8 shows the variation of the evaporator temperature versus cooling air flow rate. The startup section represents the natural or free convection heat transfer case from the condenser, when the heat transfer moved to forced convection (air flow rate 0.31 to 1.55 m^3/min) the evaporator temperature start decreasing more. Figure 8

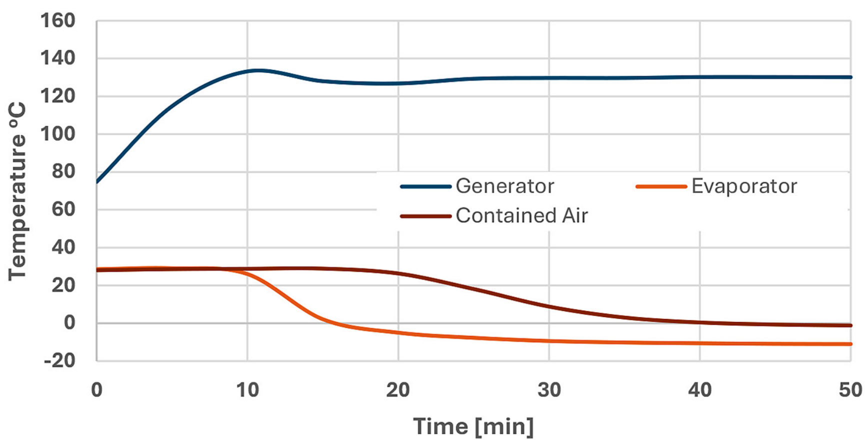

Figure 6. Contained air temperature versus time

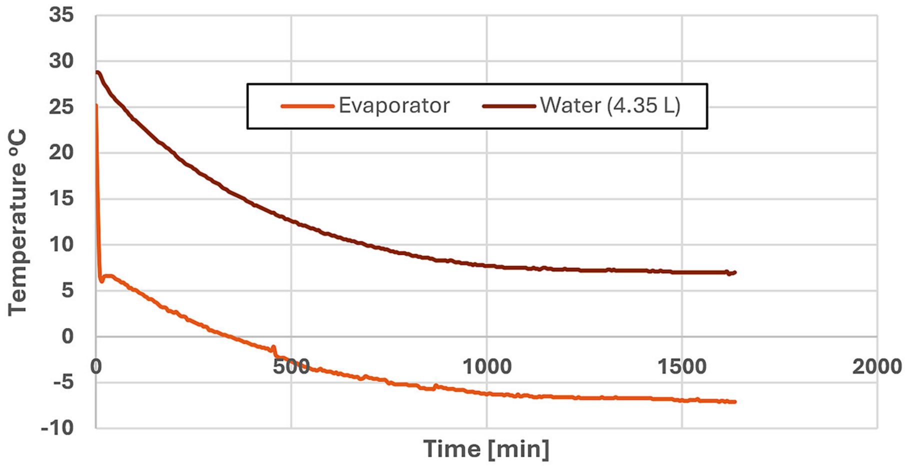

Figure 7. Contained water temperature versus time

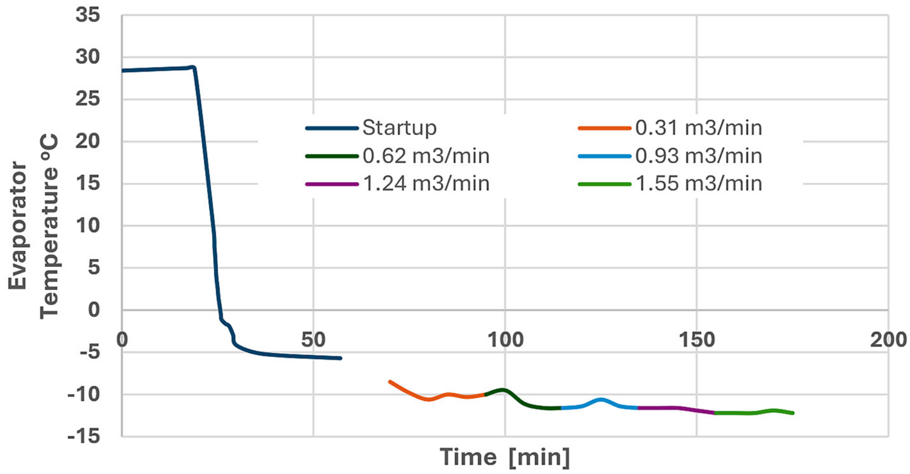

Figure 8. Temperature versus time for five different flow rates

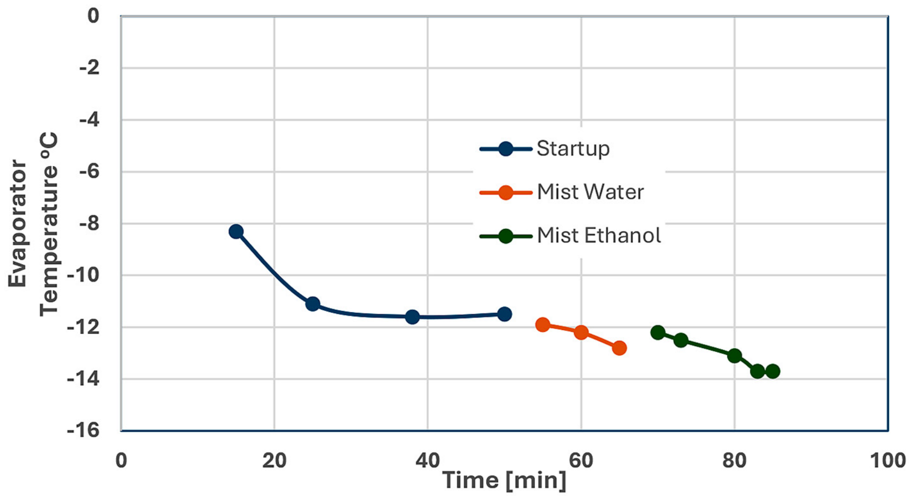

Figure 9. Evaporator temperature versus time for both water mist and ethanol mis cooling

indicates that as heat transfer from the condenser increases the evaporator temperature decreases.

It has been noted from the experimental results that the drop in evaporator temperature at the beginning say 0.31 and 0.62 m^3/min is fast and notable, whereas, at higher flow rates the temperature drops slow down.

Condenser water mist, ethanol mist cooling

As it has been noted from the cooling of the condenser by forced convection, increasing the heat transfer rate improved the evaporator temperature. In this section the effect of water mist and ethanol mist cooling techniques are explored. In the first experiment mist water was sprayed on the condenser to have evaporative cooling and maximize the rate of heat transfer.

The effect of water mist and ethanol mist cooling of the condenser on the evaporator temperature is illustrated in Figure 9. The water mist cooling increases the heat transfer from the condenser and positively affect the evaporator temperature with extra temperature drop to 12.8 °C. When ethanol mist is used in the experiment a sudden raise of the evaporator temperature was noted, this is due to the low flow of the ethanol mist which results in dry spots on the surface of the condenser, the enthalpy of vaporization of the ethanol is lower than water thus less heat can be removed from the same amount of mist ethanol. The point of using ethanol is the lower evaporation temperature, when the quantity of ethanol increases a valuable decrease in the evaporator temperature was achieved.

CONCLUSIONS

In this work three different modes of heat transfer were tested to improve the performance of the VAS used. The startup operation of the VAS under normal operation conditions showed what the evaporator reached about -9 to -10 °C and the condenser temperature of about 56 °C. The cooling load of a 6-liter contained air was tested and found a COP of about 0.31%, then cooling load of the VAS of a 4.35 liters water was tested and found an improved COP of about 15%. It shows that the VAS can be used with a higher COP when used with high heat transfer coefficient fluids. This study also analyzed moving from natural convection to forced convection heat transfer from the condenser and found that higher heat transfer rate from the condenser leads to a lower evaporative temperature. Forced convection heat transfer was able to reduce the evaporative temperature up to 12.8 °C, but as the air flow rate increases more the reduction of the evaporator temperature slows down. In this study the mist water and mist ethanol cooling were tested on the performance of the VAS. Using higher heat transfer techniques improves the workability of the VAS was concluded

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