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# A thermodynamic analysis of a transcritical cycle with refrigerant mixture R32/R290 for a small heat pump water heater

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ABSTRACT

In this study, a thermodynamic analysis on the performance of a transcritical cycle using azeotropic refrigerant mixtures of R32/R290 with mass fraction of 70/30 has been performed. The main purpose of this study is to theoretically verify the possibility of applying the chosen refrigerant mixture in small heat pumps for high temperature water heating applications. Performance evaluation has been carried out for a simple azeotropic mixture R32/R290 transcritical cycle by varying evaporator temperature, outlet temperature of gas cooler and compressor discharge pressure. Furthermore, the effects of an internal heat exchanger on the transcritical R32/R290 cycle have been presented at different operating conditions. The results show that high heating coefficient of performance ($COP_h$) and volumetric heating capacity can be achieved by using this transcritical cycle. It is desirable to apply the chosen refrigerant mixture R32/R290 in small heat pump water heater for high temperature water heating applications, which may produce hot water with temperature up to 90 °C.



## 1. Introduction

As well known, an air-source heat pump water heater (HPWH) based on the vapor-compression refrigeration cycle has wide residential and commercial applications for its outstanding energy-saving performance. Over the past decades, conventional refrigerants such as HCFCs and HFCs have been used extensively in heat pump fields owing to their excellent chemical and thermodynamic properties. However, the increasing attention to environmental problems such as global warming, ozone depletion and atmospheric pollution has led to a large number of studies related to the selection of environmentally friendly refrigerants and refrigerants mixtures as working fluids for HPWH applications in recent years. Current research and industry trends show that HCFCs and HFCs will gradually be replaced by HFC mixtures or by natural refrigerants such as carbon dioxide, propane, ammonia and so on [1].

Carbon dioxide ($CO_2$) is receiving renewed interest as an efficient and environmentally friendly natural refrigerant in heat pump applications, including heat pump water heater, space heating and heat pump dryers [2]. In this field, the transcritical $CO_2$ cycle technology has been extensively studied in many respects such as cycle modifications, component or system design and performance evaluation [3–6]. On the other hand, the use of natural refrigerant propane is also proposed and actually used in small heat pump and refrigeration systems [7–9]. Propane has no ozone depletion potential (ODP) and extremely low global warming potential (GWP), and also thermodynamic and transport properties are very similar to the HCFCs and HFCs currently used in heat pump or refrigeration systems. Of course, the main drawbacks of propane are flammable and the safety factors in handling relatively large charge quantities, which need to be specially considered. In fact, attempts have been made to develop such applications by using enhanced compact heat exchangers, optimizing system designs, reducing the charge of systems and establishing rules and regulations for the safety precautions [10,11]. The use of HFCs mixtures in heat pumps cycle has also grown in recent years. Some of the HFCs mixtures such as R410A and R407C have been applied to certain applications as substitutes for R22. Furthermore, the mixtures composed of HFCs and HCs (hydrocarbons) such as R134a/R290, R32/R290 and R417A (R125/R134a/R600) are also suggested as the drop-in or mid-term alternative working fluids for the refrigeration and heat pump system [12–14]. This kind of mixtures has the merits of decreasing the hydrocarbon flammability and of improving the cycle performance of the refrigeration and heat pump system. Also, $CO_2$/propane mixtures have been considered for use in an air-conditioning system and their performance potentials were evaluated experimentally [15]. In addition, the study of heat pumps using the transcritical vapor-compression cycle with other natural refrigerant and HFC refrigerant have also been carried out by some researcher [16,17]. Generally, transcritical cycle is thought to be more suitable for high temperature heating heat pumps, since the heat rejection process at

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**Nomenclature**

| | |
|---|---|
| COP | coefficient of performance |
| $h$ | specific enthalpy (kJ kg$^{-1}$) |
| $p$ | pressure (kPa) |
| $q_e$ | refrigerating capacity per unit of mass (kJ kg$^{-1}$) |
| $q_h$ | heating capacity per unit of mass (kJ kg$^{-1}$) |
| $q_{hv}$ | heating capacity per unit of swept volume (kJ m$^{-3}$) |
| $t$ | temperature (°C) |
| $v$ | specific volume (m$^3$ kg$^{-1}$) |
| $w$ | specific work of compressor (kJ kg$^{-1}$) |
| $\eta_s$ | isentropic efficiency |
| $\pi$ | pressure ratio |

*Subscripts*

| | |
|---|---|
| $d$ | compressor discharge |
| $e$ | evaporator |
| $o$ | outlet of gas cooler |
| 1–4 | state points of refrigerant |

a supercritical pressure introduces a gliding temperature character that may increase the cycle COP through matching the temperatures of the working fluid against those of heat transfer fluids.

As the global environment is progressively concerned, greenhouse warming has also become very important these days besides the ozone depletion issue. One of the ways to alleviate greenhouse warming is to adopt the mixtures with low GWP and develop high efficiency refrigeration and heat pump devices. From this point of view, the refrigerant mixture R32/R290 with zero ODP and relatively lower GWP could be possible alternative working fluid that can meet this need in HPWH applications. In this study, a case study of performance of a transcritical cycle with binary mixtures R32/R290 is conducted by thermodynamic calculation. The intention of this study is to show the possibility of applying the chosen refrigerant mixture in small heat pumps for high temperature water heating applications. Through this study, we hope that it could provide some useful data for the promising development of such HPWH in the future.

## 2. Transcritical cycle with refrigerant mixture R32/R290

From the theoretical side, R290 is a pure HC which offers excellent thermodynamic properties, good compatibility with most materials already presented in refrigeration systems, null ODP and extremely low GWP. R32 is HFC refrigerant, its ODP is zero, and its GWP is much lower than other HFCs such as R125, R134a and R143a. At present, R32 is commonly used as one of the components of R407C and R410A. Table 1 shows the basic properties of R290 and R32. It can be seen that R290 belongs to safety group A3, but R32 belongs to A2. Therefore, the degree of flammability of the mixture R32/R290 is clearly lower than that of only R290, especially in the case of the higher concentrations of R32. On the other hand, since the mixture R32/R290 is proposed to be employed in small capacity heat pump, the risks of flammability can be reduced by decreasing the amount of refrigerant mixture in the system. Furthermore, special precautions may be applied to reduce the risks under normal operation. In reality, this fact is reflected in the regulations and research projects for the heat pump with R290 [9]. That is the reason why the mixture R32/R290 has been introduced in the present paper.

Vapor–liquid equilibrium data for the mixture R32/290 have been reported over a wide range of temperature and composition, which shows azeotropic behavior at R32 mol fraction ranging from 0.635 to 0.683 depending on temperature [14,18]. For the mixture R32/R290 with the azeotropic compositions, the critical temperature may have a minimum point. The critical temperature and the critical pressure for mixture R32/R290 with mass fraction of 70/30 are estimated at 61.5 °C and 4.7644 MPa, respectively [19]. Considering this point, the azeotropic mixture R32/290 is also proposed as the promising alternative refrigerant for the heat pump cycle.

The critical temperature of the azeotropic mixture R32/R290, as shown in Table 1, implies that both subcritical and transcritical cycle operations are possible for an HPWH application. In subcritical cycle operation, as known from common vapor-compression cycle, the temperature of heat rejection is low. Consequently, this gives the limitation to high temperature heating. In transcritical cycle operation, on the contrary, heat is rejected with a certain temperature-glide as the working fluid undergoes a continuously increase in density, from a vapor state to a liquid-like dense-gas state. This makes the process more suitable for high temperature heating where the desired hot-water delivery temperature can be achieved by matching the temperatures of the working fluid against those of the heated water through a counter flow heat exchanger. In addition, it can be seen that the critical pressure of the azeotropic mixture is lower than that of $CO_2$. Therefore, it is possible that the operating pressure of the transcritical cycle system using the azeotropic mixture is not too high compared with the refrigerant $CO_2$.

Fig. 1 shows a schematic diagram of a simple azeotropic mixture R32/R290 transcritical cycle composed of an evaporator, gas cooler, compressor, expansion valve and internal heat exchanger. The cycle is characterized by operation around the critical point for the mixture, with a supercritical high-pressure and a subcritical low-pressure. As shown in Fig. 1, this transcritical cycle consists of a non-isentropic compression process, an isobaric heat rejection process, an adiabatic expansion process, and an isobaric evaporation process. In the pressure–enthalpy diagram, the process path 1–2–3–3′–4–4′–1 represents the cycle with internal heat exchange.

In order to obtain meaningful results from the transcritical cycle calculation with R32/290, the thermodynamic performances of the cycle are evaluated based on thermodynamic cycle analysis method. Steady flow energy equation and mass balance equation have been employed in each individual process of the cycle. Also the following assumptions have been made to simplify the analysis:

1. Heat transfer with the ambient is negligible.
2. Compression process is adiabatic but non-isentropic.
3. Evaporation and gas cooling processes are isobaric.
4. Throttling process is adiabatic.
5. Vapor is at saturated or superheated condition at the exit to the evaporator.

The detailed characteristics of the cycle can be found as follows:
Heating capacity per unit of mass

$$q_h = h_2 - h_3 \quad (1)$$

**Table 1**
The properties of R290 and R32.

| Refrigerants | Molecular formula | Critical temperature (K) | Critical pressure (MPa) | Security | ODP | GWP |
|---|---|---|---|---|---|---|
| HC290 | $CH_3CH_2CH_3$ | 369.38 | 4.25 | A3 | 0 | 20 |
| HFC32 | $CH_2F_2$ | 351.31 | 5.81 | A2 | 0 | 880 |