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# Experimental analysis on a novel solar collector system achieved by supercritical $CO_2$ natural convection

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ABSTRACT

Solar collector has become a hot topic both in scientific research and engineering applications. Among the various applications, the hot water supply demand accounts for a large part of social energy consumption and has become one promising field. The present study deals with a novel solar thermal conversion and water heater system achieved by supercritical $CO_2$ natural circulation. Experimental systems are established and tested in Zhejiang Province (around N 30.0°, E 120.6°) of southeast China. The current system is designed to operate in the supercritical region, thus the system can be compactly made and achieve smooth high rate natural convective flow. During the tests, supercritical $CO_2$ pipe flow with Reynolds number higher than 6700 is found. The $CO_2$ fluid temperature in the heat exchanger can be as high as 80 °C and a stable supply of hot water above 45 °C is achieved. In the seasonal tests, relative high collector efficiency generally above 60.0% is obtained. Thermal and performance analysis is carried out with the experiment data. Comparisons between the present system and previous solar water heaters are also made in this paper.



## 1. Introduction

Solar collector technology has become a hot topic with the increasing demand of new generation sustainable energy sources in recent years. The global society is in demand of increasing energy supply and the fossil fuels/sources now in use are exporting vast $CO_2$ and other harmful emissions at the same time. Both government and industrial sectors are now trying to reduce emissions and improve technological innovations. In search of renewable and clean energy/technology, solar collector has been proved to have promising applications in water heating, refrigeration, water desalination, space heating/cooling, heat pumps, combined energy supply, etc. It is reported that both in developed countries and developing countries solar water heating technology can be one economical choice for its simplicity as a renewable source [1–4]. Solar water heater has obtained a vast market all around the world and nearly two thirds of installations are located in developing countries such as China, India, Africa and mid-America countries. But it also has challenges regarding system efficiency and scaling effect, the combination with other technologies, feasibility for different occasions, cost and compact system design, etc.

Solar water heater can be categorized as one low temperature solar thermal system without concentration of solar radiation. In recent years, a lot of studies have been carried out and the main focus laid on the improvement of collector efficiency considering absorber plate design, selective coatings, thermal insulation, tilt angle of collector, working fluids, specific geometric design, etc. [5–7]. Review on the status of development in solar water heating technologies has also been made [8–10]. Later, a thorough review on solar thermal collectors and applications in both industry and domestic fields came out [11], which include various kinds of collectors' development including applications in home aspects and engineering cycles. Other most recent reviews on solar collector water heater can also be found in the reference [9]. In those reviews, due to the widespread applications evacuated tube solar heater is mostly studied and the challenges focused on the flat plan collector efficiency [12–15].

Among those improvements mentioned above, working fluid is often discussed as one important factor affecting heat exchanger efficiency and flow friction factors in the collector. In recent years, as one substitute working fluid, carbon dioxide has been more and more proposed in energy conversion cycles and systems. In history $CO_2$ has been used as a working fluid in air conditioning and marine refrigeration earlier in 20th century and then replaced by CFC/HCFCs. However, in recent years $CO_2$ has been put forward again due to the obvious ODP (Ozone Depletion Potential) effect of CFC/HCFCs and other environment problems emerged, which

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**Nomenclature**

| | |
|---|---|
| $A$ | projected area of the collector ($m^2$) |
| $C_p$ | specific heat (J/(kgK)) |
| $C_{p,W}$ | specific heat of water (J/(kgK)) |
| $h_{CO_2,out}$ | enthalpy of $CO_2$ fluid at outlet of solar collector (J/kg) |
| $h_{CO_2,in}$ | enthalpy of $CO_2$ fluid at intlet of solar collector (J/kg) |
| $h$ | heat transfer coefficient ($W/(m^2K)$) |
| $HX$ | heat exchanger |
| $I$ | solar radiation ($W/m^2$) |
| $I_t$ | total solar radiation during the test time ($=\int IAdt$) |
| $L$ | length (m) |
| $\dot{m}_{CO_2}$ | mass flow rate of $CO_2$ (kg/s) |
| $\dot{m}_W$ | Mass flow rate of water (kg/s) |
| $Nu$ | Nusselt number |
| $P$ | pressure (MPa) |
| $Pr$ | Prandtl number |
| $Q_C$ | collected heat quantity of solar collector (W) |
| $Q_H$ | recovered heat quantity of hot water (W) |
| $Re$ | Reynolds number |
| $T$ | temperature (°C) |
| $T_a$ | ambient temperature |
| $T_f$ | fluid temperature at collector inlet |
| $T_{W,out}$ | water temperature at the outlet of heat exchanger (°C) |
| $T_{W,in}$ | water temperature at the inlet of heat exchanger (°C) |
| $\Phi$ | diameter (mm) |
| $\eta_C = Q_C/(IA)$ | solar collector efficiency (%) |
| $\bar{\eta}_{Collector}$ | averaged collector efficiency (%) |
| $\eta_{REC} = Q_H/Q_C$ | heat recovery efficiency (%) |

has become one central topic in the World Climate Change Conferences since late 20th century. $CO_2$ is non-toxic and with negligible ODP and GWP (Global Warming Potential). In fact, utilizing $CO_2$ can also be seen as one kind of CCS (Carbon Capture and Storage/Sequestration) measures [16,17]. In addition, $CO_2$ has its advantages as a unique natural working fluid: when it goes near the critical point ($T_C$ = 304.13 K and $P_C$ = 7.38 MPa) the thermal–physical properties experience dramatic changes even the temperature/pressure change only a little, especially for density and specific heat. In order to make use of this advantage, a lot of thermal systems have take $CO_2$ as new generation working fluid [18,19]. The most famous representative can be the *Eco-cute* $CO_2$ heat pump water heater, which has earned a data of more than 3 million units now in commercial use in Japan, where the problem of high pressure, safety and maintenance has been successfully treated. Other related representative study can be found in $CO_2$ heat pump water heater [20,21], trans-critical $CO_2$ solar Rankine systems [22–24] both theoretically and experimentally, where good heat transfer and fluid flow condition is maintained.

Based on the previous research and experimental tests in solar collector systems using supercritical $CO_2$ cycles [25], the present study propose a novel supercritical $CO_2$ solar water collector by natural circulation. Such kind of natural circulation based solar collector is less studied compared with forced convection kind [9]. Utilizing the high natural convective efficiency of supercritical $CO_2$ working fluid, high circulation rate and compact system can be achieved due to the critical changes of fluid status across the collector panels, thus to win its potential advantages over traditional collectors. With good specific heat changes and large density difference induced of supercritical $CO_2$ fluid, relatively high temperature flow as well as high Re number flow can be seen in natural convection condition [17]. Related studies have shown the high collector fluid temperature and effective natural convective flow induced in supercritical $CO_2$ systems [20–29] and formerly a series of other studies [30–35] proved supercritical/trans-critical $CO_2$ natural convection can achieve high Reynolds flow even in very small heat sink and source temperature differences (and also the system performance and natural circulation characteristics, natural circulation stability analyzed), which can be useful information for the development of supercritical $CO_2$ natural circulation systems now in process. In addition, for relatively low pressure $CO_2$ natural convection, analytical and numerical studies on the circulation system parameters optimization methods are also reported [36–38].

The present study is also one continuation of our previous experimental studies of trans-critical experimental study on $CO_2$ solar water heater [25] and preliminary natural experimental prototype solar water heater [5]. Based on the first preliminary test in Yokohama area in Japan [5], a novel solar collector system is then developed and tested in Zhejiang Province (around N 30.0°, E 120.6°) of China. Compared with traditional collectors, the current system is designed for supercritical fluid with separate cycles of working fluid and water cycles. The two cycles are: one is the supercritical $CO_2$ cycle, in which $CO_2$ is naturally heated through evacuated tube collector and cooled in the heat exchanger; another is the water cycle, in which water is heated through heat exchanger by supercritical $CO_2$ fluid in the first cycle, then water is stored in a hot water tank. It should be noted that the density difference in supercritical $CO_2$ cycle can be very large and thus much high Reynolds number flow can be achieved compared with water and other liquid natural flows [5,25], which is one major difference that respect for the relative high efficiency found in present study as well as previous ones. Another difference from traditional ones is the evacuated tube design and coating/integration process, which allows high solar absorption rate and good panel-fluid heat transport. In addition, by using supercritical $CO_2$ natural flow, no expansion/compression/pumping apparatus is needed, so system efficiency, system compactness and low cost [6–11] in natural collectors can be achieved at the same time. One previous study has shown the supercritical $CO_2$ solar collector preliminary flow rate relation with solar radiation and reported system efficiency above 60.0%, which is much higher that natural water kind [25].

In this paper, fundamental tests results of novel supercritical $CO_2$ solar collector are reported. The basic system performance and optimization analysis based on system parameters are also discussed and comparisons are also made with previous related studies. In the following parts, experimental set ups are first introduced, then basic system behavior and theoretical analysis with collected data, after that optimization and discussions are made. It is hoped that the results can be useful for future new generation solar collector research and engineering designs.

## 2. Experimental setup

### 2.1. Formation of model

Based on the natural convection supercritical $CO_2$ solar water heater concept put forward in this study and our previous designs [5], a new experimental prototype is established. As shown in Fig. 1(a), the new model has no pumping devices and is mainly consisted of two parts: the supercritical $CO_2$ solar collector circulation system and the water heating and control system. The supercritical $CO_2$ natural collector side has three parts: (1) evacuated tube solar collector panel; (2) supercritical $CO_2$ – water heat exchanger; (3) pressure control valve mounted between the heat