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Thermal-hydraulic process for cooling, heating and power production with low-grade heat sources in residential sector

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ABSTRACT

A new process based on thermal-hydraulic conversion actuated by low-grade thermal energy is investigated. Input thermal energy can be provided by the means of solar collectors, as well as other low temperature energy sources. In the following article, "*thermo-hydraulic*" term refers to a process involving an incompressible fluid used as an intermediate medium to transfer work hydraulically between different thermal operated components or sub-systems. The system aims at providing trigeneration energy features for the residential sector, that is providing heating, cooling and electrical power for meeting the energy needs of domestic houses. This innovative system is made of two dithermal processes (working at two different levels of temperatures) and featuring two different working fluids. The first process is able to directly supply either electrical energy generated by an hydraulic turbine or drives the second process thanks to the incompressible fluid, which is similar to a heat pump effect for heating or cooling purposes. The innovative aspect of this process relies on the use of an hydraulic transfer fluid to transfer the work between each sub-system and therefore simplifying the conversion chain. A model, assuming steady-state operation, is developed to assess the energy performances of different variants of this thermo-hydraulic process with various heat source temperatures (80–110 °C) or heat sinks (0–30 °C), as well as various pairs of working fluids. For instance, in the frame of a single-family home, located in the Mediterranean region, the working fluid pairs (R1234yf/R1233zd) is investigated in detail in order to estimate the annual performances. For domestic houses, the process aims at amplifying the solar energy collected by a factor of 1.32 for heating purpose, provides a cold production with a coefficient of performance of 0.4 and generates electricity from the remaining solar energy with an efficiency of 3.7%, reducing the electrical or auxiliary consumption and overall greenhouse gas emissions.
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1. Introduction

The main conclusion of the 5th report of the "IPCC" (Intergovernmental Panel on Climate Change) [1] notes that a global temperature increase exceeding 2 °C would have dramatic and irreversible consequences on the environment. The residential and tertiary sectors are the most important energy consumers in Europe: they account for more than 40% of the final energy [2] and are responsible of 11.5% of GHG (GreenHouse Gas) emissions [3]. Therefore, both sectors have drawn attention in the recent EU 2030 framework for climate and energy policies, which aims at reducing GHG emissions by 40% by increasing the part of renewable energies in the current energy mix and increasing the global energy efficiency by 27% [4]. One part of the future solution considers to replacing the fossil fuels widely used in the residential sector by exploiting renewable energy sources to meet the various domestic needs such as heating, cooling, and electricity production. Another method consider addressing the efficiency of the current systems. Co-generation and tri-generation systems may implement both approaches for efficiently satisfying the residential needs.

Trigeneration systems (heating, cooling and electricity production) are under developed in the residential sector. However, mCHP technologies (micro Combined Heat and Power) are found more often in households based on micro designs for electricity production (< 30 kW) [5,6] as well as, reciprocating internal combustion engines [7], fuel cells [8,9], micro-turbines [10], Stirling

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Nomenclature

$\dot{q}$	heat power, W
A	surface, m^2
BS	liquid separator
C	condenser
COP	coefficient of performance
COA	coefficient of amplification
CT	transfer cylinder
E	evaporator
G	heat coefficient loss, W/(m^3 K)
GWP	Global Warming Potential
h	specific enthalpy, J/kg
HyT	hydraulic turbine
HyP	hydraulic pump
I	global solar irradiance, W/m^2
$k1$	linear heat transfer coefficient, W/(m^2 K)
$k2$	quadratic heat transfer coefficient, W/(m^2 K^2)
M	mass, kg
ODP	Ozone Depletion Potential
P	pressure, Pa
Q	heat, J
T	temperature, K
TV	throttle valve
$T^\star$	differential temperature, K
W	power, W
wf	working fluid

Greek symbols

ϵ	heat exchanger effectiveness
η	efficiency
η_0	optical efficiency
ρ	density, kg/m^3
ϕ_w	solar gain on a vertical wall oriented south

Subscripts and superscripts

$1,2,3,4$	particular points in Mollier diagram relative to receiver cycle
a,b,c,d	particular points in Mollier diagram relative to engine cycle
aux	auxiliary
c	cold
$coll$	solar collector
$elec$	electric
ext	exterior
G	global
g	gaseous
gen	generator
gl	gaseous/liquid
h	hot
i,j,k	intermediary points in Mollier diagram
l	liquid
ll	liquid/liquid
m	medium
mM	medium Motor cycle
mR	medium Receiver cycle
R	receiver cycle
M	motor cycle
set	setpoint
th	thermal

engines [11] and Organic Rankine Cycles [12–14] or Kalina cycle [15]. Most of these technologies achieve a global CHP (Combined Heat and Power) efficiency greater than 80%, and several technologies are currently available on the market [16]. Their heat sources are mostly provided by fossil fuels and guarantee temperatures ranging from 150°C to 200°C in order to improve their thermodynamic efficiency. However, some applications using renewable energy remain under study and start reaching the required level of technological maturity for their commercialization. More researchers are also interested in the valorization of heat sources below 100 °C [16–20] with the global target to make them attractive from an economical point of view, including solar energy, geothermal energy or waste heat uses which remains largely under-exploited.

This active research area is in constant progress to use low-grade thermal energy. The cooling technologies using renewable energies [21,22] relies on different approaches such as sorption process (absorption and adsorption processes) [23], desiccant cooling [24], thermochemical systems [25] and combined Organic Rankine Cycles with vapor compression cycle (ORC-VCC) using one [26–28] or two different working fluids [29]. Most of these cooling processes remain at the experimental stage and only ad/absorption systems currently achieve a significant level of market penetration. Some of the above-mentioned CHP solutions have begun to be investigated as combined cooling, heating and power systems (CCHP) [30–32]. Various methods have been explored [16] but two approaches in particular show promising results. The most studied one consist of coupling a mCHP process with thermally activated cooling technologies, mainly ab/adsorption processes [30,33]. The second approach consists of producing work to set into motion a heat pump ensuring heating in winter and cooling in summer. For example, linking photovoltaic panels (PV panels) with dual-purpose heat pumps remains the best way to achieve trigeneration with standard industrial components [34,35]. Nevertheless, other methods such as combined heat pumps and ORC have been investigated [36,37], but their main limitation remains the global efficiency of the overall conversion chain.

Thermo-hydraulic systems, which produce work from heat in order to compress another fluid, could simplify this conversion chain [38,39]. Various companies and laboratories are currently investigating this concept using different technologies, such as liquid piston [40] or thermofluidic oscillator [41]. The originality of our study relies on the use of an hydraulic transfer fluid in the frame of a trigeneration thermal system. Thermo-hydraulic processes may present an original solution for heating/cooling and electricity production: they achieve high exergetic efficiencies and are particularly suited for exploiting low-temperature heat sources. Among these possible sources, the seawater surfaces in tropical area, also called ocean thermal energy conversion application (OTEC) [39], or heat conversion systems driven by flat plate solar collectors could be seamless potential candidates. In addition, the continuous increase of energy prices could lead these technologies to become competitive from an economical point of view and to come to new cogeneration and trigeneration applications. Our study aims at examining this new process, determining the suitable pair of working fluids and finally, evaluating its annual performances in a Mediterranean climate.

2. Thermohydraulic process for trigeneration

2.1. Principles of the CHV3T and CAPILI subsystems

In this article, thermo-hydraulic refers to a process based on the conversion of thermal energy into work involving an

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