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Research Paper

R290 (propane) and R600a (isobutane) as natural refrigerants for residential heat pump water heaters ☆

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HIGHLIGHTS

- A HPDM model has been used to evaluate the performance of hydrocarbon as refrigerants for HPWH applications.
- The UEF and FHR have been used to evaluate the performance of R134a, R290 and R600a refrigerants.
- Different condenser wrap patterns and storage tank thermal insulation effectiveness have been consider.
- The impact of compressor discharge temperature, water stratification has been evaluated.
- The impact of saturation temperature change in condenser and total refrigerant charge has been evaluated.

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ABSTRACT

Growing awareness of the potential environmental impacts of various refrigerants has led to the phase-down of hydrofluorocarbon (HFC) refrigerants and to initiatives replacing HFCs with hydrocarbons or other environmentally friendlier fluids. This study evaluated the performance of R290 (propane) and R600a (isobutane) as substitutes for R134a (a HFC) for heat pump water heating (HPWH). A component-based model (calibrated against the experimental data) was used to predict the performance of the HPWH system. Key performance parameters such as unified energy factor, first hour rating, condenser discharge temperature, thermal stratification in the water tank, and total refrigerant charge were investigated. Analysis results suggest that both alternative refrigerants could provide comparable system performance to that of the baseline system containing R134a, with one caveat. As a drop-in alternative, R290 was found to be a better substitute for R134a, whereas R600a is expected to provide similar performance if the compressor size is increased to provide similar heating capacity. Significant reductions in system charge and lower condenser discharge temperatures were identified as additional benefits.

1. Introduction

Residential and commercial water heating accounts for approximately 10% of all residential and commercial site energy usage in the United States, making it the fourth largest energy end use in homes [15]. On a global scale, in 2015 water heating consumed about 15–20% of residential energy for OEDC and non-OEDC countries as shown in Fig. 1.

Despite recent advancements in energy efficiency, most residential water heaters are either conventional natural-gas-fired or electric storage heaters. While such systems are quite simple, they have very low system efficiency. Conversely, under appropriate conditions, electrically driven, vapor compression heat pumps, or heat pump water heaters HPWHs), represent a system opportunity with much higher thermal efficiency than conventional electric water heaters, resulting in significant energy savings [1]. Similar to conventional refrigeration or air-conditioning cycles, HPWHs use a vapor compression refrigeration cycle to transfer heat from a low temperature ambient to a high temperature reservoir, a hot water tank. A traditional heat pump is highly complex, as a selection of components (evaporator, compressor, etc.) plays a critical role in the overall efficiency of the system [10,5]. When such a system is used to heat water, the design becomes even more

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Nomenclature

$\alpha_{1,2,\ldots,10}$	mass flow coefficients for compressor
$\beta_{1,2,\ldots,10}$	power coefficients for compressor
ΔP_{tp}	pressure drop (Pa)
Δx	change in mass vapor quality
ρ	density (kg/m^3)
v	specific volume (m^3/kg)
λ	thermal conductivity (W/(m-K))
μ	viscosity (N s/m^2)
c_p	specific heat (J/kg-K)
d	internal tube diameter (m)
D_c	fin collar outside diameter (m)
D_h	hydraulic diameter (m)
f	friction factor
$f_{1,2,\ldots6}$	correlation parameter
$j_{1,2,\ldots6}$	correlation parameter
F_s	fin spacing (m)
g	acceleration due to gravity (m/s^2)
G	mass flux (kg/m^{2}s)
h_{LG}	latent heat of vaporization (J/kg)
j	Colburn factor
L	tube length (m)
N	number of longitudinal tube row
Nu	Nusselt number
P_l	longitudinal tube pitch (m)
P_t	transverse tube pitch (m)
Pr	Prandtl number
Re_D, Re_{Dh}	Reynolds number based on hydraulic diameter
R_{mix}	correction factor for advection
S_h	height of slit (m)
S_n	number of slits in enhanced zone
S_s	breadth of a slit in the direction of airflow (m)
T_{avg}	average temperature (K)
T_{cond}	condensation temperature (K)
T_{evap}	evaporation temperature (K)
T_{sat}	saturation temperature (K)
T_w	wall temperature (K)

Subscript

f	fluid
g	vapor
in	inlet
out	outlet

Acronyms

AHRI	Air-conditioning, heating, and refrigeration institute
CFC	chlorofluorocarbon
CFD	computational fluid dynamics
COP	coefficient of performance
EF	energy factor
FHR	first hour rating
GWP	global warming potential
HC	hydrocarbon
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
HPDM	Heat Pump Design Model
HPWH	heat pump water heater
HVAC&R	heating, ventilation, air conditioning, and refrigeration
ODP	ozone depletion potential
OEDC	Organization for Economic Cooperation and Development
UEF	unified energy factor
WH	water heater

complicated, as the addition of other components (e.g., condenser configuration, water storage tank, thermal insulation) can directly impact system performance [25,26,35,40,20,4].

Numerous studies have evaluated the thermal performance of HPWH systems with varying levels of complex details including working fluid, thermodynamic cycle, tank size, and water draw rate. A range of different analysis methods have been deployed, including energy analysis, entropy analysis, and exergy analysis for individual components and the whole system [51,19]. It has been concluded that the coefficient of performance (COP) is affected by many factors, such as environmental conditions, working fluid, refrigerant charge level, expansion device control, water tank, compressor frequency, and so on as reported by Hepbalsi and Kalinci [24].

A key parameter of interest is the working fluid used in the vapor compression cycle. Conventional HPWH systems deployed R-22, which is being phased down due to the high ozone depletion potential (ODP) associated with this fluid. R-134a emerged several years ago as the potential replacement, and most manufacturers have introduced systems with a reasonably higher unified energy factor (UEF) based on this refrigerant. However, concerns about possible global climate change have led to legislative action all around the world to phase down the use of hydrofluorocarbons (HFCs), including R-134a, in a range of heating, ventilation, air

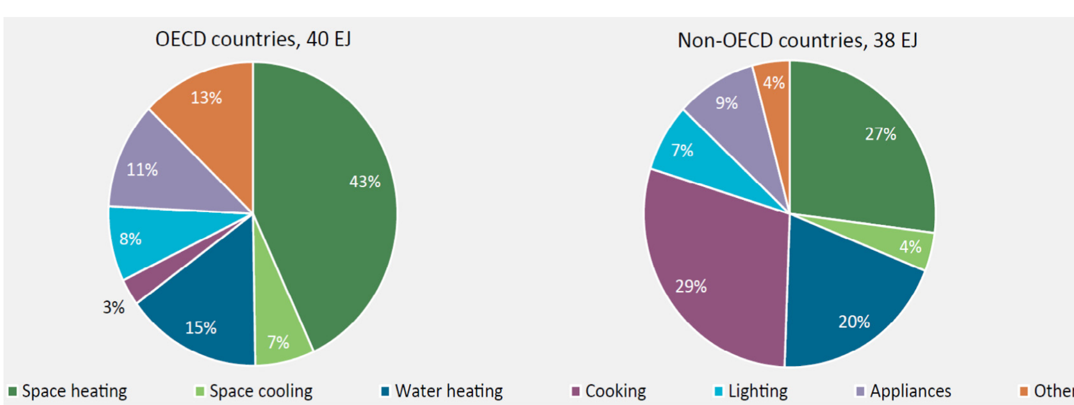

Fig. 1. End uses of residential energy consumed in OECD and non-OECD countries [17].