Applied Thermal Engineering 138 (2018) 807–818

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Parallel loop configuration for hybrid heat pump – gas fired water heater system with smart control strategy

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HIGHLIGHTS

- The new control strategy for parallel loop hybrid system has been provided.
- ~10% to ~60% operation economic benefits can be achieved for −12 °C to 20 °C ambient.
- Fuel price ratio of electricity to gas have a heavy influence on hybrid performance.
- Typical cities in China are investigated for cost saving and environmental impact.

ARTICLE INFO

Keywords:
Parallel loop
Hybrid system
Heat pump water heater
Gas fired water heater
Economic benefit
Control strategy

ABSTRACT

Air source heat pumps suffer from reduced thermal delivery in cold climate conditions. In this study, the parallel loop hybrid system with the combination of heat pump and gas fired water heater in one device is provided as the sustainable alternative to alleviate such issues. An economic-based new control strategy has been proposed for the hybrid system to investigate the system thermal performance and reveal the economic benefits for residential space heating application. The climate conditions, fuel source price ratio and gas heater thermal efficiency have been included in the analysis of the hybrid performance. Under the operating map, the control strategy can lead to a ~10% to ~60% system operating economic benefits for space heating application for −12 °C to 20 °C ambient. Raising the price ratio can decrease the ratio of the heat delivered by the heat pump on the overall heat loading, especially for higher final water target temperatures. Lowering the price ratio can improve the energy process saving potential (% gas heater heating mode baseline). In addition, several typical cities have also been investigated as a part of studies for hybrid performances and environmental impacts.

1. Introduction

Buildings, as the huge consumers of over one-third of all final energy and half of the electricity at the global scale, account for approximately one-third of global carbon emissions [1,2]. Among the building sectors, residential sector encompasses ~70% of the global buildings [3], and recent studies and surveys indicate that space and water heating demands take up ~80% of energy use in residential sector in Europe and 60% in the United States [4], and ~40% in northern China [5]. However, the ever-increasing fuel consumption of heating and domestic hot water has been growing dramatically, along with the potential fuel source shortage in recent years, driving the environmental awareness to the forefront of the concerns for the society. The conventional heating systems in some countries, such as China, are mainly based on the fossil fuel (coal) burning, creating immense greenhouse gas (GHG) emissions and serious air pollution. Taking into account the current level of atmospheric CO_2 and its impacts on human welfare, there is the increased need for the development of more efficient heating systems as the sustainable alternatives to mitigate CO_2. The air source heat pump (ASHP) is considered to be a visible, energy-efficient and environmental friendly alternative to conventional heating systems. During winter, low ambient temperatures can result in the phenomenon of frosting over the evaporator coils and large pressure ratio, and this can make the heating performance drop dramatically, which can heavily restrict its applications. In addition, the heavy reliance on the electricity for the heat pump can also add the burden of high electricity demand, leading to increasing risks for the electrical grid. Thus researchers conducted extensive studies of improving the coefficient of performance (COP) of the ASHPs, including various hybrid energy options for the building applications [6].

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https://doi.org/10.1016/j.applthermaleng.2018.04.087
Received 14 January 2018; Received in revised form 14 March 2018; Accepted 16 April 2018
Available online 22 April 2018
1359-4311/

Nomenclature

Abbreviations

COP	coefficient of performance
GHG	greenhouse gas
ASHP	air source heat pump

Symbols

Q	heat delivery [kW]
m	main stream water flow rate [kg/s]
m_{HP}	heat pump water flow rate [kg/s]
m_{gas}	gas heater water flow rate [kg/s]
C_P	specific heat of water [kJ/kg·K]
T	water temperature [°C]
Y_{elec}	fuel price for electricity [RMB/kW·h]
Y_{gas}	fuel price for natural gas [RMB/kW·h]
$COST$	energy process cost for loads [RMB/h or RMB/season]
η	thermal efficiency of the gas heater [1/1]
W	Power consumption [kW]
HR	ratio of the heat delivered by the heat pump to that of the whole loads [1/1]
ξ	energy saving potential compared to gas heating only as the baseline [%]

Subscripts

Amb	ambient
HP	heat pump
gas	gas heater
initial	initial state
final	final state
Max	maximum
Min	minimum
Elec	electrical, electricity
Tot	total
optimal	optimal
sys	system
n	total number of temperature intervals

Studies on working fluids, new heat pump circulation system, cycle modification, system coupled with solar energy or energy storage systems, optimal control, and defrosting technologies have been widely developed. Dong et al. [7] proposed R407c in solar integrated ASHP on the heating performance. In the average outdoor dry-bulb temperature range of −9 °C to −11 °C, the integrated average part load is 14.9% higher than the conventional ASHP, while the seasonal average part load value can be 15.5% higher than the conventional one. Other studies [8] conducted a novel quasi-two-stage compression system coupled with ejector using R290 as the working fluid. The results showed that it could lead to the increase of 2.8–3.3% and 6.4–8.8% for heating COP and capacity compared to the case of quasi-two-stage compression system with subcooler, 1.1–2.0% and 3.2–6.0% compared to the case of quasi-two-stage compression system with flash tank. In addition, more experimental work is needed to be conducted. Hu et al. [9] proposed a self-optimizing control scheme for maximizing the COP of an air-source transcritical CO_2 heat pump water heater. Li and Yu [10] modeled a flash tank cycle based ASHP heater with lumped parameter and revealed that the optimum for allocating the thermal conductance inventory could help maximizing the system heating COP. Zhang et al. [11] developed and analyzed the heat pump defrosting performance with capturing the heat dissipated by the compressor, and an increase of 1.4% can be achieved for the system COP. Wang et al. [12] conducted one study of ASHP heater coupled with a heat exchanger, coated by a solid desiccant with an energy storage unit, and the results indicated that the system COP could be increased by 17.9% and 3.4% in comparison to reverse-cycle defrosting under ambient condition −3°C and 3 °C, respectively. Wang et al. [13] provided some suggestions for modification of current defrosting control strategies to avoid the mad-frost issues based on their tests. Zhang et al. [14] performed the ASHP heating tests in cold regions in northern China and suggested that, in order to obtain an acceptable COP, the temperature difference between indoor and ambient should be controlled within 41 °C. Li et al. [15] investigated the direct-expansion of solar-assisted heat pump water heater, and provided some suggestions for improving the system efficiency, especially for the bare flat-plate solar collector as an evaporator. Thermal energy storage based on reverse cycle defrosting method can also help achieve improved indoor thermal comfort, with a shorter defrosting period and a higher indoor supply of air temperature during reverse cycle defrosting [16]. Long and Zhu [17] proposed a design of a

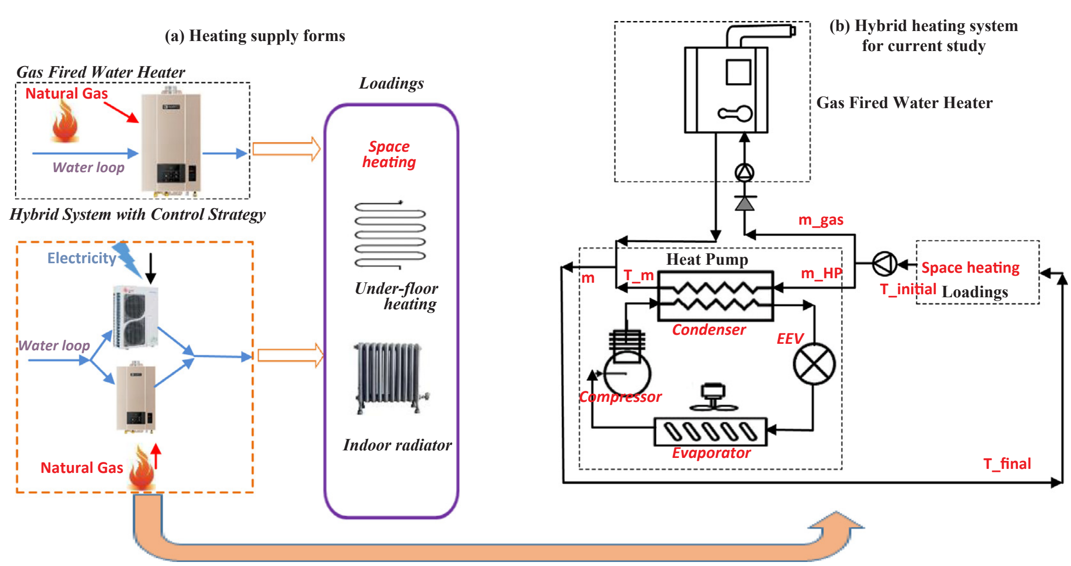

Fig. 1. Schematics of hybrid heat pump and gas fired water heater system.