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Analysis of the performance of a tankless water heating combo system: Space heating only mode

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ABSTRACT

Advancements in water heating and control technology have improved the performance of tankless water heaters in recent years. A tankless water heater coupled with a hydronic air-handling unit functions as a novel system known as a combination system that is used for residential space heating. To quantify the effect of the outlet water temperature from the water heater on the time-averaged thermal efficiency of a tankless water heater-hydronic heater combo system, an experimental method was developed. With the experimental assembly, it was found that the thermal efficiency of the tankless water heater during space heating varied monotonically between 39% and 95% for outlet water temperatures settings respectively between 38 °C and 60 °C. Energy losses from the flue gases represented 3%–47% of the total energy that was supplied to the system for the same respective outlet water temperature settings. An exergy analysis of the air handling unit was performed and results are presented. The results suggest tankless water heater-hydronic air heater combo systems can be an efficient configuration for space heating at tankless heater outlet water temperature settings of 60 °C. Water temperature settings below 60 °C produced transient variations, including cycling, in the system that became important and system performance deteriorated.

1. Introduction

In Canada, an estimated 50% of residential homes use natural gas locally as the primary energy source for space heating [1]. Developments in the heating, ventilation, and air-conditioning (HVAC) industry have led to alternative systems to the conventional furnace and "boiler" or tank water heater arrangement. A heat exchanger built into an air handling unit (AHU) that is coupled with a tankless water heater (TWH[1]) is a novel system in which hot water for domestic use and space heating can be provided on-demand and simultaneously. This system is also capable of providing domestic hot water (DHW) and space heating as independent functions. This system is known as a combo system or alternatively, an integrated appliance system. The combo system for space heating presents a unique advantage in that users are able to exhibit control over the temperature of the air delivered for space heating through modulation of the TWH water outlet setting controller. The ability to independently control the water temperature and influence space heating allows the combo system increased flexibility in performance when considering consumer comfort and safety.

Incorporating a TWH into the system as opposed to **storage water heaters** (SWHs) is advantageous due to the elimination of heat loss from stored hot water. To meet hot water demand, SWHs heat and maintain a reservoir of water at a set temperature whereas TWHs will heat water on-demand and as required by the end user. Typical TWH energy factors range from 0.80 to 0.83 [2] compared to SWH, in which energy factors range between 0.55 and 0.63 [3]. Since TWHs do not have a reservoir capacity, these units are ideal for steady-state operation as the thermal efficiency is not affected by the number of hot water draws [2].

The performance of natural gas fired TWH for the provision of DHW under various operating and initial conditions has been thoroughly studied. Glanville et al. [2] studied the short-term performance and intermittent behavior of various TWH models to quantify and better explain the deviations between the actual and rated performance of TWHs. The investigators expanded a previously developed single node model and showed that actual daily DHW usage is not accurately represented in test methods found in TWH ratings. **As well**, in short term operation, performance is adversely affected by several factors become influential including: pressure drop, start-up delay and outlet temperature fluctuations [2]. Grant et al. [4] studied TWH response to rapid changes in water flow rate and temperature-flow conditions and determined that rapidly changing flow rates through the TWH can

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[1] Tankless water heater.

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Nomenclature

c_p	Specific heat capacity (kJ-kg^{-1} K^{-1})
$\dot{E}$	Rate of energy (kW)
$\dot{H}$	Rate of total enthalpy (kW)
h	Specific enthalpy (kJ-kg^{-1})
h_f°	Specific enthalpy of formation (kJ-kg^{-1})
s	Specific entropy (kJ-kg^{-1} K^{-1})
$\dot{S}$	Rate of entropy (kW-K^{-1})
$\dot{W}$	Rate of electrical work (kW)
$\dot{Q}$	Rate of heat loss (kW)
X	Mass fraction
$\dot{m}$	Mass flow rate (kg-s^{-1})
$\dot{V}$	Volumetric flow rate (m^3-s^{-1})
LHV	Lower heating value (kJ-kg^{-1})
t	Time (s)
T	Temperature (°C)
$E\dot{x}$	Rate of exergy (kW)

Greek Symbols

η	Efficiency

Subscripts

CV	Control volume
in	Inlet
out	Outlet
gen	Generated
ng	Natural gas
ca	Combustion air
cg	Combustion products
a	Air (at ambient)
ra	Return air
sa	Supply air:
avg	Average
0	Dead state (298 K, 1 atm)
i	Species
I	First law
II	Second law (exergy)
v	Water vapour in stack
f	Flue gases in stack

reintroduce undesirable temperature perturbations to the system. Furthermore, Dieckmann et al. [5] found that the thermal efficiency of the TWH was sensitive to the frequency of hot water draws; however, these studies have focused on analysing the performance of the TWHs independent of other equipment. Thus, few studies have been undertaken to determine the thermodynamic efficiency and performance of a TWH as the heating plant in a combo system for space heating applications.

Previous work relating to combo systems has focused on developing a linear input-output energy model for a variety of domestic hot water (DHW) heating appliances and hydronic systems [6]. This study assessed the performance of several combination systems including: boilers with internal coils, boilers with an indirect DHW tank, SWH tank that was used for space heating, and a boiler with separated DHW storage tank [6]. The systems were tested under different loading conditions and the study developed methodologies to investigate the impact of system input parameters on annual performance. A laboratory study performed under the U.S. Department of Energy's Building America program found that heating plant steady-state efficiency decreases with increasing inlet water temperature to the heating plant units [7]. Additionally, a field study performed in Hennepin County, MN, USA found that the maximum efficiency of a combination system operating for space heating with a TWH surpassed the maximum observed efficiency for a combo system with a boiler or SWH by 2% or 3%, respectively [8].

Currently, no studies address the steady-state efficiency of combo systems that includes a natural gas TWH as the heating plant for space heating mode only. The paucity of research in this area will negatively affect the market penetration rate of combo systems given that there is inadequate information on performance or potential cost savings [9]. Furthermore, current industry standard ratings of the heating plant appliances, such as energy factor, do not represent the expected thermal efficiency for the overall combo system [9,10]. The current Canadian standard for combo systems, CSA P9-11, which provides a rating that is analogous to an energy factor rating, focuses on aggregated metrics such as thermal performance factor rating [11]. This standard focuses on anticipated usage profiles and seeks to quantify the performance of the combo system based on various demand schemes as opposed to being tested to current test methods for the individual components.

Quantification of key thermodynamic parameters will establish a baseline for anticipated performance of combo systems from a building science and thermal engineering perspective. A study on the thermal efficiency of such systems will provide valuable insight and guidance to industry and consumers regarding combo TWH-hydronic heater systems for use in residential buildings. Therefore, the objectives of this study were to quantify the effect of varying TWH water outlet line temperature to the AHU in order to determine: (1) time-averaged first law thermal efficiency, (2) time-averaged AHU exergy efficiency, and (3) thermal energy losses through the flue gases during steady-state operation.

2. Background

Fig. 1 shows a schematic and process diagram of a combo system configured for both space and domestic hot water (DHW) heating for residential application. The TWH water outlet line separates into two lines: one that connects directly to the AHU (the AHU inlet water line) and another line for DHW draws (DHW line). The DHW line is plumbed to the piping network of the residence to provide heated water to end users at: faucets, showers and for other appliances that require hot water. Alternatively, the TWH outlet water line can be used to supply heated water for an in-floor heating. For combo system in space heating mode, the water line inlet to the AHU was plumbed to an internal heat exchanger in the AHU. Downstream of the AHU, the outlet water line from the AHU was connected to a cold-water feed supply line, and mixed water was routed back to the TWH (the TWH inlet water line) if the hot water and space heating are occurring simultaneously. In space heating operation only, the water loop of the system was closed and no cold feedwater was added to the system nor was hot water removed from the system for DHW usage. For this case, the outlet water line from the AHU was the inlet water line to the TWH. Similarly, the inlet water line to the AHU can be considered the outlet water line to the TWH.

In principle, AHUs can operate in cooling and heating modes. However, in the combined system configuration of this study, the AHU only operates in heating mode and thus only the space heating modality was studied. For space heating applications, a circulator (pump) in the AHU activates when there is a request for heating. Activation of the TWH occurs when the minimum activation flow rate is surpassed and heated water from the TWH outlet water line is pumped to the AHU inlet water line. The heated water passes through a header in the AHU where the heated water entered a staggered-tube finned bank heat exchanger. An air blower draws return air from the space and causes the air to pass over the heat exchanger and move to the supply duct.