COMMERCIAL CO_2 HOT WATER HEAT PUMP FIELD TRIALS

H.J. Huff, Research Engineer/Scientist
T. Sienel, Principle Engineer/Scientist
Y.K. Park, Research Engineer/Scientist

United Technologies Research Center, East Hartford, CT, USA

ABSTRACT

United Technologies Research Center, under contract to the US Department of Energy, is performing pre-commercial field trial testing of a commercially sized heat pump water heating system using CO_2 as the working fluid. This system has a nominal capacity of 60 kW and performance of 3.5 COP at 10ºC water inlet temperature and 10ºC ambient air temperature. As such, the system is suitable for hotels, restaurants, cafeterias, dormitories, hospitals, laundromats, and many other commercial and industrial applications. The system is described and operational experience and economics from field trial sites is presented.

Key Words: ***heat pump, carbon dioxide, transcritical, commercial water heater.***

1 INTRODUCTION

The goal of this effort has been to effectively reduce the barriers to broad application of heat pump water heaters in the US. Through market research, these barriers have been found to be (1) Reliability, (2) Customer Value, and (3) Infrastructure. Reliability is extremely important to the customer, and as heat pump systems are inherently more complex than the existing gas and electric systems, this has traditionally been very challenging. To address this, a reliability growth tracking model has been developed (Sadegh et al. 2004) and is being populated with field trial experience. These experiences, through the reliability model, will be used to improve the system design. The customer value proposition is a measure of how economically attractive the system is for a potential customer, and will vary from site to site. The fundamental issues to be addressed are the performance (both capacity and efficiency) and cost of system to the customer. The use of CO_2 as the working fluid allows the system to achieve higher efficiency levels than traditional HFC based heat pump systems as well as allowing the system capacity to remain high even under low ambient temperature operating conditions. Cost reduction is achieved by using a standard high volume small chiller platform as the basis of the heat pump design. The final barrier to be addressed is the infrastructure, which relates to the ability of a potential customer to get information on the system, find a dealer and installer, and provide for service and aftermarket support. For this, a large company with nationwide presence is needed, which UTC is in a good position to provide.

The field trials are run in two phases, with three system designs developed over the life of the project. The first field trial (Phase I) commenced in the 4th quarter of 2004, and was developed from a CO_2 heat pump water heater currently in European field trials. There are three deployed units in this field trial, which will run to the 4th quarter of 2006. Modifications to the basic design achieved a functional system capable of running under 60Hz and relevant to UL requirements. Phase II field trials have commenced in the 2nd quarter of 2005, and have included system improvements intended to optimize the unit for 60Hz operation as well as moving closer to full UL listing. There are an additional five deployed units in this phase of the field trial, which will also run to the fourth quarter of 2006. The final design will come after a full teardown analysis of the eight field trial units and will include all lessons learned from the field trial experience to improve reliability and cost effectiveness.

In order to generate the most relevant information for reliability improvement, a broad selection of field trial sites is essential. This necessitates the selection of field trial sites which push the operational envelope of the unit. Examples of the type of variability desired in the field trial selection include duty cycle (continuous vs. cycling), temperature extremes (hot and cold), and building integration (indoor vs. outdoor). Every attempt has been made to select field trials with as broad a range of these parameters as possible, while also providing good operational economics to the field trial host.

2 HOT WATER PUMPS

Together with the reinvention of CO_2 as refrigerant (Lorentzen 1994), heat pumps were identified as potential applications for transcritical vapor compression systems. The temperature glide of the refrigerant during the heat rejection process allows better matching of the refrigerant temperature with the secondary fluid compared to sub-critical cycles. The pinch point, the smallest temperature difference in the heat exchanger, which limits the efficiency of the cycle, occurs at the refrigerant outlet of the heat exchanger. Consequently, the refrigerant can be cooled to the lowest possible temperature before entering the expansion device, which benefits the cycle performance. In sub-critical cycles on the contrary, the refrigerant rejects heat during condensation at a constant temperature level, which results in a large average temperature difference between the refrigerant and the secondary fluid. The heat transfer across large temperature differences increases the irreversibility associated with the heat transfer. The pinch point in sub-critical cycles typically occurs at the onset of the two-phase region in the heat exchanger at much higher temperatures than the inlet temperature of the secondary fluid. The benefits of transcritical heat pumps have been analyzed by numerous authors (Lorentzen 1994, Reiberer et al. 1997, Saikawa et al. 1997) Hwang and Radermacher 1998, Neksa et al. 1998, Bullard et al. 2000, Reiberer et al. 2000, Neksa 2002, Luca et al. 2003, Bullard and Rajan 2004).

3 TECHNOLOGY

The design capacity of the unit is 60 kW at a rating point of 10ºC ambient temperature and a water inlet temperature of 10ºC. The capacity of the system is equivalent to approximately 1000 liters per hour of 60ºC sanitary water, at a design target efficiency of COP = 3.5. The unit provides 400 to over 1300 liters of hot water per hour at ambient temperatures between –20 ºC and 46 ºC. The design is based on Carrier's Aquasnap chiller series. The unit shares all components except for those in direct contact with the working fluid with the commercial product line. The utilization of high-volume production components allows a cost saving design and reduces the reliability risks associated with new component development. Fig. 1 shows a picture of the unit.

3.1 System Set-Up and Control

Fig. 1 shows a schematic of the system design of the heat pump. The unit is approximately 1.30 m high, 1.06 m deep, and 2.08 m long. The heat pump operates as once-through water heater with the storage tank as buffer between the unit and the water main line. The water in the storage tank is stratified, which allows a more energy efficient operation than mixed storage tanks.

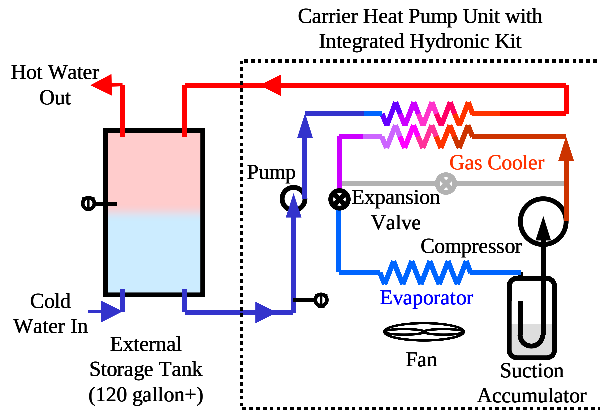

Fig. 1. Hot water heat pump and system set-up.

The temperature sensor in the middle of the storage tank triggers the on/off cycle of the heat pump. A microprocessor controls the electronic expansion valve to accommodate an optimum discharge and suction pressure depending on water and air temperature. The control board is based on the design of commercial chiller and is equipped with a communication board. The unit can be remotely monitored and controlled via Carrier Comfort Network, which also allows collecting and transferring data via a data line.

4 FIELD TRIAL UNITS

In Phase I of the US Department of Energy contract three units were installed and operated in the field. Two field trial units are installed indoors, and one outdoors. The outdoor unit is installed at the main campus of United Technologies Research Center in Connecticut. The unit provides hot water to the cafeteria of the Research Center. The remaining units are installed in Alabama to provide process water to a paraplast process and to a laundry facility in a hospital.

4.1 CO_2 Hot Water Heat Pump for Paraplast ProcesS

The paraplast process requires periodic hot water supply at temperatures greater than 80 ºC during a manufacturing process that produces thermoplastic aerospace components. The primary purpose of this field trial is to subject the heat pump unit to large numbers of on/off cycles in order to collect reliability data under extreme conditions. The hot water demand of the field trial facility averages to 3800 liters per day with peaks of 27 liters per minute. The facility is equipped with an electric water heat of 125 kW capacity. The field trial heat pump is installed to provide base load capacity and preheating. Fig. 2 shows a schematic of previous the set-up without heat pump and the modified system with CO_2 hot water heat pump. The integration reduces the power demand on the electric heater and at the same time guaranties hot water supply even if the CO_2 heat pump fails. As an additional benefit, the CO_2 heat pump supplies cold air from the evaporator to the building where it is installed. The building has to be air-conditioned constantly to remove heat from the paraplast process. The cooling capacity comes as a “free” benefit and reduces the load on the chiller system of the facility.

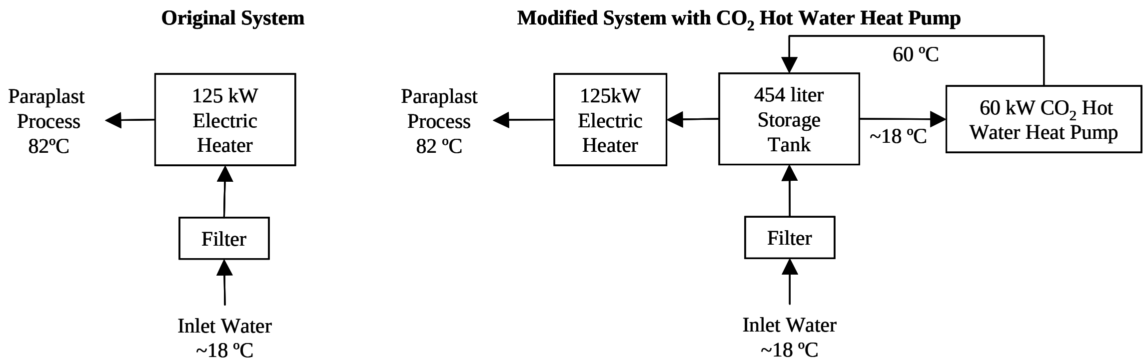

Fig. 2. CO_2 hot water heat pump integration in paraplast process.

The average total daily energy consumption of the original system with electric heater alone is approximately 284 kWh. The projected total daily energy consumption of the modified system with CO_2 heat pump pre-heat and electric heater is 154 kWh of electricity, 53 kWh consumed by the CO_2 heat pump and 98 kWh consumed by the electric heater. The heat pump will provide 186 kWh of heating capacity with an energy consumption of 53 kWh of electricity. The cooling capacity provided to the building averages to 50 kWh per day if a 10 SEER chiller system is assumed as baseline. The annual energy savings of the CO_2 heat pump add up to approximately 38,300 kWh. The energy savings translate to a reduction of electricity costs of $1,150 per year at an average price of electricity of 3 cents per kWh. While the cost benefits for this application are limited, the operational experience gained during the field trial provides valuable input to the reliability data of the unit.

4.2 CO_2 Hot Water Heat Pump For Hospital Laundry Facility

Laundry facilities in hospital have a considerable demand for sanitary hot water. The field trial site operates in a 16-hour shift and utilizes 250,000 liters of hot water per day. The water is heated by steam, which is generated in a dual fuel furnace with approximately 80% efficiency. The hot water is stored in an open tank. A float in the tank opens the water line from the city supply if the tank level falls below the set point. The fresh water is heated in a once-thorough steam heat exchanger. A pump circulates the water in the tank through a steam heat exchanger if the tank temperature falls below set point. The CO_2 heat pump is integrated into the system to provide a small fraction of the base load of the facility. Fig. 3 shows a schematic of the CO_2 heat pump integration. A solenoid valve controls the water supply from the heat pump storage tank. The valve opens if the water level in the open tank is below the set point and if the water temperature in the storage tank is above a certain level. The float in the open tank first opens the solenoid from the heat pump storage tank before it opens the water inlet to the steam water heater. This set-up guarantees that the system takes full advantage of the cost and energy savings from the CO_2 heat pump, while providing reliable hot water supply to the laundry facility.

The primary purpose of this field trial is to collect performance and reliability data of the unit under constant load conditions. Due to the utility price structure in the region of the hospital, the cost for gas, oil, and electricity are approximately 4 cents per kWh independent of the energy source. This price structure is one of the reasons why the southeast of the US is one of the primary traditional markets for electric heat pumps. The annual energy cost savings average to $10,400 at an average cost of 4 cents per kWh gas/oil/electric.

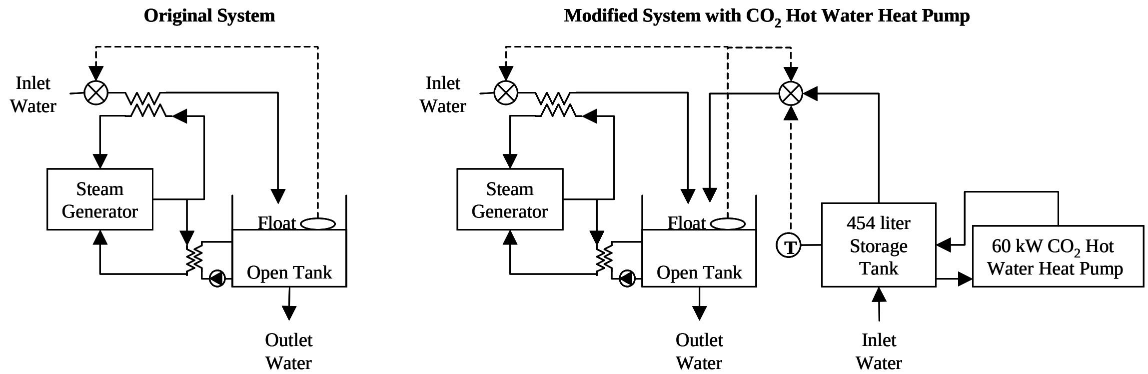

Fig. 3. CO_2 hot water heat pump integration in hospital laundry facility.

4.3 CO_2 Hot Water Heat Pump For Cafeteria

A field trial unit is installed at the cafeteria of United Technologies Research Center in Central Connecticut. The cafeteria serves approximately 400 meals per day and has an annual water usage of approximately 5400 m^3. Fig. 4 shows the integration of the CO_2 heat pump with the original steam heater for the hot water supply. Before the heat pump installation the hot water was generated by the building steam supply. After the installation of the heat pump, the building steam supply provides peak load and backup during maintenance caused outages of the heat pump. The dashed lines in Fig. 4 indicate signals to normally closed valves, and the dotted line indicates a signal to a normally open valve. The heat pump is controlled by a thermistor in the 454 liter storage tank. If the hot water level in the storage tank falls below the set point, the unit will start generating hot water.

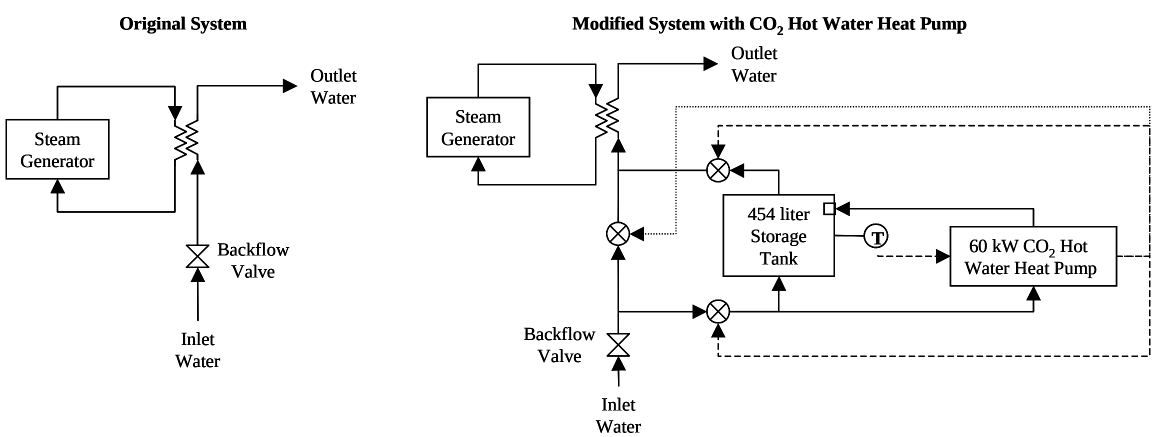

Fig. 4. CO_2 Hot water heat pump integration for cafeteria.

5 CONCLUSIONS

Pre-commercial field trials of a commercially sized CO2 heat pump water heater have been installed in three diverse application sites as part of a US Department of Energy funded project to reduce the barriers to introduction of heat pump water heater technology in the US. These installations suggest that a compelling customer value proposition exists for heat pump water heaters with sufficiently high performance and low cost. Operational experience from these sites as well as five new sites will be presented at a later date.

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