Development of Thermally-Driven Ground Source Heat Pump Concept

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Abstract: This paper outlines design considerations and initial results from the development of a thermally-driven Ground Source Heat Pump concept, targeting residential and small-commercial applications. This concept employs a novel Binary Fluid Ejector (BFE) technology. The BFE-GSHP is projected to offer operating cost savings versus baseline heating and cooling systems and, in most regions, versus conventional electrically-driven GSHPs as well. As a thermally-driven compression process, COP is inversely proportional to compression ratio, therefore an application with a steadier and smaller temperature lift ($T_{cond} - T_{evap}$) is better suited for a BFE system. This makes a ground source heat pump system more suitable than an air source heat pump system for BFE space heating and cooling applications.

Key Words: ejector compression, ground source heat pump

1. INTRODUCTION

The driving force of all refrigeration cycles is compression of the refrigerant, most commonly achieved via an electromechanical compressor. As opposed to direct application of mechanical work, whereby electricity or engine shaft work drives a vapor compression cycle, thermally-driven (TD) refrigeration cycles offer an alternative with a significant potential for primary energy and cost savings, by driving the process with direct-fired combustion, solar thermal, and/or waste heat. These TD refrigeration cycles, deployed as heat pumps, refrigeration, or air-conditioning, are driven by “thermal compressors,” compressing a low pressure vapor refrigerant from the evaporator and delivering a high pressure vapor refrigerant to the condenser. The main form of TD refrigeration cycle currently commercially available is the vapor absorption cycle. These systems utilize a "thermal compressor” rather than an electrically-driven mechanical compressor, though the remaining system components are common across all refrigeration cycles. However, the absorption-system thermal compressor itself necessitates four additional system components, and an additional fluid (the absorbent), adding system complexity versus a mechanically-driven cycle.

The most widespread TD refrigeration cycle commercially is the vapor absorption cycle, in which the refrigerant (often ammonia or water) is compressed by a relatively small electromechanical pump, as a liquid in solution with the absorbent. Lifting the pressure of a liquid versus a vapor requires significantly less energy, for example comparing a 1.3 $COP_{heating}$ ammonia-water heat pump to an 8.2 HSPF vapor compression heat pump, the TD refrigeration cycle solution pump requires less than 1.0% of the total energy input to the electric compressor [1]. The thermal energy input is required to drive the refrigerant vapor out from its absorbed state in the generator (or “desorber”). As adequate

refrigerant/absorbent pairs require high affinities and stability over a wide range of temperatures and pressures, they have significant heats of absorption. When operating in heating mode, this heat can be recovered in addition to that rejected at the condenser, however while in cooling mode this heat must be rejected.

TD refrigeration cycles were developed and commercialized prior to vapor compression cycles. For example, ice production in the late 19th century was primarily driven by ammonia-water vapor absorption cycles prior to common use of electromechanical vapor compression system [3]. After widespread electrification and the development of internal combustion engines, electro-mechanical vapor compression cycles now comprise of over 90% of all air-conditioning systems in residential, commercial, and industrial applications [2].

1.1 Ejector Refrigeration Cycles

A historically popular TD refrigeration cycle, particularly for sites that had access to an inexpensive source of steam, was ejector refrigeration. Ejectors, also known as eductors, were simple devices for entraining a low pressure fluid from a reservoir with a high pressure fluid to pump to a mixed pressure. These ejectors work on the hydrodynamic principle that a high pressure jet in a quiescent fluid will entrain the surrounding fluid through turbulent mixing along the shear boundary. Ejectors are often applied as pumps for liquids and gases or agitators for stored fluids, particularly where pumping the fluid by electromechanical means may present an explosion hazard.

Their initial popularity owes to their simple operation, shown in Figure 1, whereby the drive fluid enters a nozzle at “A”, exiting and creating a region of low pressure as the jet expands. This jet entrains the refrigerant fluid from point “B” as secondary flow, and the resulting mixed flow exits the diffuser at point “C” at an elevated pressure. In thermodynamic terms, the ejector converts the potential energy (pressure) of a motive fluid (drive fluid) to kinetic energy in order to entrain a suction fluid (refrigerant), and then recompress the mixed fluids by converting kinetic energy back into potential energy (pressure). As the primary flow is typically supersonic, the jet nozzle is converging-diverging to limit upstream propagation of pressure waves. As they have no moving parts, ejector pumps are maintenance-free and do not require lubricants. They are often applied where reliability is critical (e.g. nuclear power stations, vehicles) and where caustic & dangerous fluids are transported (e.g. petrochemical plants).

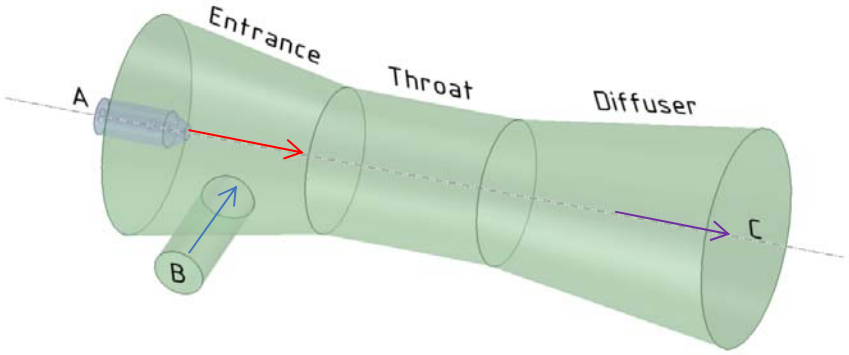


Figure 1: Diagram of Standard Ejector Compression

As part of a TD refrigeration cycle, ejector compression is a natural extension of the ejector pump, a reliable and proven method of compressing vapor refrigerant. In traditional ejectors, as developed from the late 19th Century into modern times, both the drive fluid and refrigerant were most commonly water, where high pressure steam as primary flow would entrain and compress low pressure steam exiting an evaporator, providing cooling for large buildings. The “thermal compressor” for these systems consists of a generator (or boiler) which uses a

thermal input to boil and pressurize the drive fluid within the ejector, and a relatively small pump which moves a quantity of fluid from the condenser back to the generator.

Typical ejector HVAC applications involve the use of a single working fluid and waste heat or heat from other renewable sources to produce heating, cooling or refrigeration [4]. In addition to steam as the working fluid, traditional and emerging refrigerants have been used where low grade waste energy is available. For HVAC applications, ejector system COP are low: between 0.2 and 0.4 for cooling (by comparison vapor absorption TD refrigeration cycles can exceed 0.7 and vapor compression cycles can exceed 6.0 on a site energy basis). Where low grade energy is unavailable, a standalone ejector TD refrigeration cycle is typically uneconomical. However, ejectors are commonly deployed as an energy recovery device during the refrigerant expansion step of mechanical vapor compression cycles, particularly when refrigerant selection requires high operating pressures (i.e. CO_2) [3].

1.2 Binary Fluid Ejector Concept

Ejector refrigeration cycles suffer low cyclic efficiency when operating with a single working fluid, because one fluid cannot simultaneously have the ideal qualities of a drive and refrigerant fluid. For the refrigerant, a high phase change enthalpy is desirable for near isothermal heat transfer at the evaporator/condenser; in contrast the drive fluid should have a low phase change enthalpy to promote ready phase change within the boiler. Additionally, the drive fluid should have a greater molecular weight than that of the refrigerant to improve the ejector entrainment ratio. To address these competing goals, ejector cycles have been developed to handle two dissimilar fluids with different latent capacity and molecular weights.

Through the late 1980's to the mid-1990's, Calmac Manufacturing, Inc. proposed a new ejector expansion refrigeration cycle (EERC). The goal of the EERC was to increase the efficiency of the cycle by recovering some of the energy lost in single fluid ejector cycles by using two immiscible fluids. The experimental system achieved a COP of 0.5, doubling the best previously reported figures, but it fell short of numbers that would make it competitive with other thermally activated cooling technologies, namely vapor absorption cycles [5].

The Binary Fluid Ejector (BFE) concept [6], currently under development by May-Ruben Technologies (MRT) uses two chemically distinct binary fluid components, which allow each of the two fluids to be optimized for their respective functions – compression and refrigeration. In addition to utilizing a suitable binary fluid pair to improve performance over standard ejector compressors, MRT does not rely on standard nozzle and ejector geometries that favor inefficient momentum exchange (turbulent shear mixing) over more efficient pressure exchange. For energy transfer from the drive fluid to the refrigerant at their interface, two transfer methods are characterized in the literature:

1) *Momentum Exchange* - Shear turbulent mixing entrainment at the interface between the primary and secondary fluids, which is always present due to velocity gradients between fluids. Overall, this is an inefficient (irreversible) means of entrainment of the secondary flow.
2) *Pressure Exchange* - Dynamic pressure force interaction at the interface between the primary and secondary fluids, whereby the high pressure bulk fluid acts to compress the low pressure bulk fluid. This means of energy transfer is significantly more efficient than turbulent mixing.

MRT has identified both static and oscillating nozzle designs which have the potential for a significant improvement in compression through generation of stream-wise vortices (example shown in Figure 2).

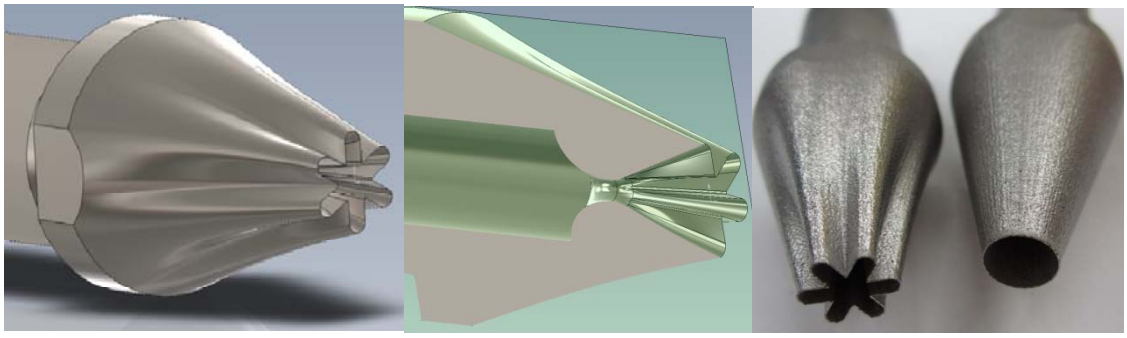


Figure 2: Graphic, Cross-Section, and Photograph of Example Advanced Nozzle Design

Another important innovation of the BFE versus prior art is the specific geometrical optimization of the geometry of the ejector nozzle and ejector body to specifically work with the binary fluid pair. [6] When binary fluids are used in a standard ejector, designed to work with a single fluid, the standard geometry will not yield top performance of the binary fluids. Much work has been done as part of the current development effort to identify key geometrical parameters and understand their effects on BFE performance.

In developing the BFE concept for distillation, a predictive computational fluid dynamics (CFD) model was developed and calibrated to an experimental ejector test rig [7,8]. The validated model was used to analyze the expected improvement in BFE performance over prior art conventional ejector refrigeration systems. For the studied application, distillation, the validated models predicted that a binary fluid mixture would exhibit a 250% improvement in the COP over the single fluid used in conventional steam jet refrigeration systems, if the Condenser and Evaporator are designed to the 5°C differential that is appropriate for distillation applications [7,8].

2. Binary Fluid Ejector-Ground Source Heat Pump Development

As with all refrigeration cycles, the cycle COP is inversely proportional to the compression ratio, therefore an application with a steadier and smaller temperature lift ($T_{cond} - T_{evap}$) is better suited for a BFE system. Due to its technical fit, the authors initially are focusing on a BFE TD ground source heat pump (GSHP) concept, shown in Figure 3.

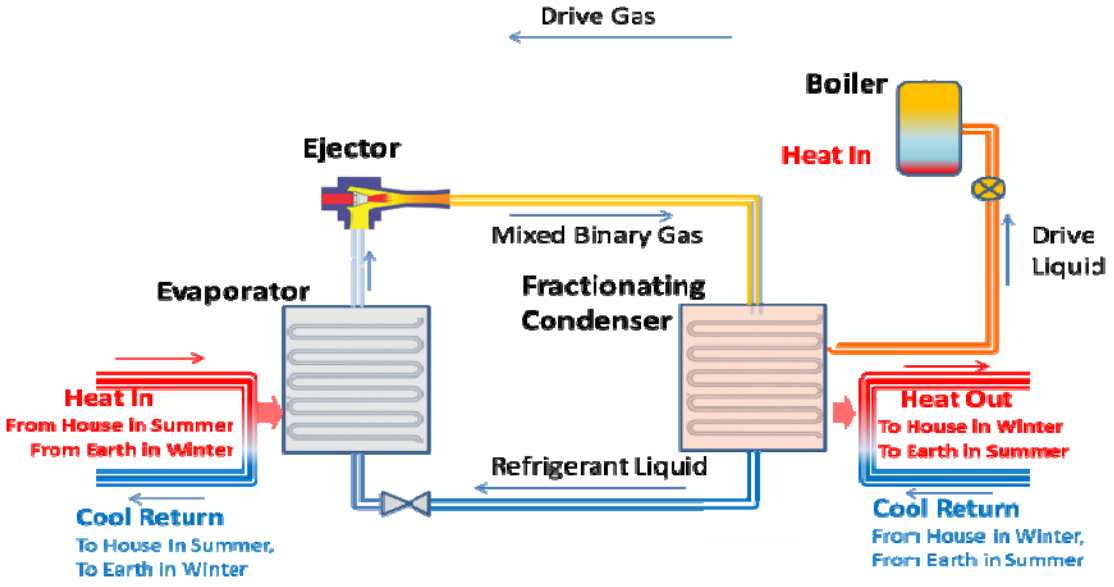


Figure 3: Diagram of Concept BFE TD-GSHP

GSHPs as a solution for high-efficiency heating and cooling are well established, particularly in the U.S., which hosts almost two thirds of installed systems in the U.S. and continued steady growth is predicted. Of the one million installed GSHPs in the U.S., the average size is 3 RT and half are residential applications [9], thus the target TD-GSHP market is small commercial and residential applications (2-10 RT). This is a market segment which has been difficult for absorption chillers to penetrate because their capital cost per RT is high for such smaller systems. As a simple system, the BFE-GSHP will have few moving parts and will not require the use of refrigerants that contribute to ozone depletion or global warming through fugitive emissions. If successfully commercialized, the BFE-GSHP will be suitable for the various climate zones where standard GSHPs are installed, flexible in its thermal input (solar, waste heat, natural gas, etc.) and capable of seasonal operation.

2.1 Estimation of BFE-GSHP Opportunity

Driven by a natural gas-fired boiler, residential-sized BFE-GSHP system performance will depend on the local and seasonal operating conditions. However, early simulation and experimental validation by MRT on its distillation application of the BFE technology suggest that system heating and cooling COPs may exceed 2.0 and 0.9 respectively when extrapolated to temperature lifts typical for GSHP [7,8]. Though not yet validated through experimentation, recent modeling work specifically for the GSHP application (i.e. using working fluids tailored for the temperature lift), suggest that these are conservative assumptions. Compared to baseline heating and cooling systems (a 13 SEER Central A/C system and a 78% AFUE warm-air furnace), and average installed electrically-driven GSHPs (an equivalent performance of 15 SEER cooling and 3.9 COP heating [9]), the opportunity of a BFE-GSHP varies greatly with regional heating/cooling loads [10] and the cost of electricity versus natural gas [11].

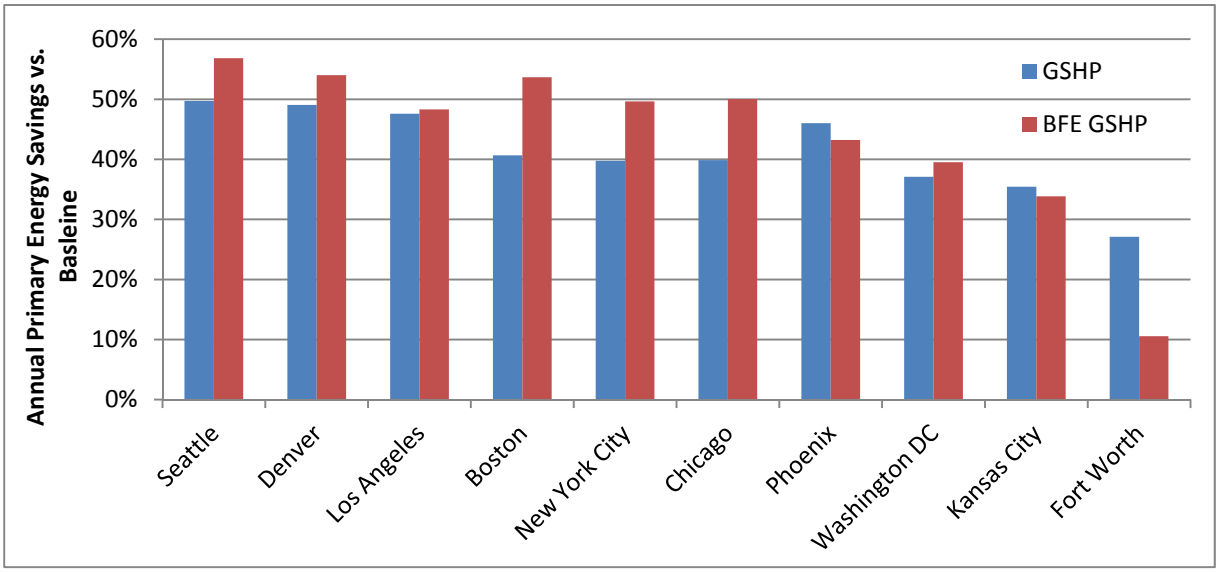


Figure 5: Estimated Annual Primary Energy Savings vs. Baseline

Using regional primary-to-site energy conversion factors [12], Figure 5 shows the potential annual primary energy savings versus the baseline heating/cooling systems for the standard electric ground source heat pump and the BFE-GSHP for several U.S. Cities, ordered by increasing annual cooling load from left to right. In general, for locations with a greater heating load versus cooling load, the BFE-GSHP offers nominally higher primary energy savings. Figure 6 highlights the estimated operating cost savings, which shows that in regions with a high cost of electricity relative to natural gas (e.g. Denver, CO) the BFE-GSHP yields the greatest potential savings. The standard electric GSHP yields greater savings

where electricity costs are low (Seattle, WA) and in cooling-dominant climates (Kansas City, MO). To improve installation payback periods, the concept heat pump cost target (excluding ground loop, ductwork, etc.) will have to be at parity with standard GSHPs at approximately $1,000/ton [9].

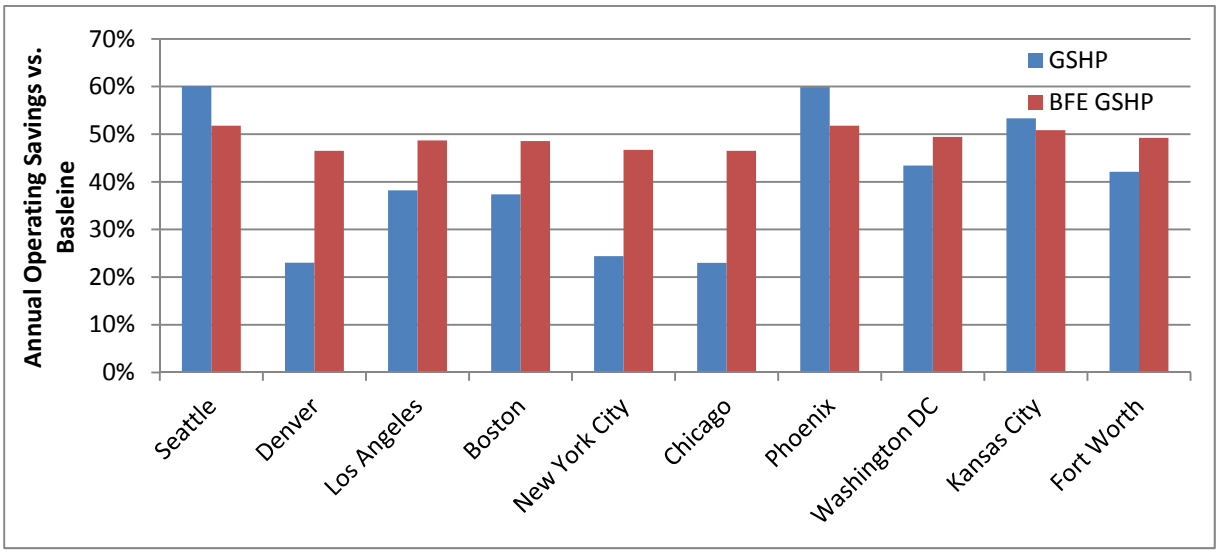


Figure 6: Estimated Annual Operating Cost Savings vs. Baseline

2.1.1 Preliminary Definition of BFE-GSHP Cyclic Performance

One advantage of binary fluid ejector refrigeration is that an array of drive fluids and refrigerants may be utilized to suit the specific application, provided the ejector and balance of system are designed appropriately. As an important step in developing BFE technology, MRT has utilized their experimental test rig and calibrated CFD modeling tools to evaluate a range of potential fluid-pairs and ejector geometries. Subsequently, preliminary modeling results for BFE use in GSHP applications indicate that the initially projected operating efficiencies are feasible. Further development is currently underway.

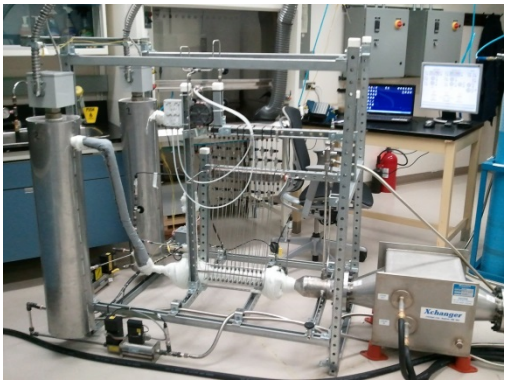


Figure 7: Experimental Ejector Test Rig

The careful selection of the working fluid pair and the ejector geometry are critical to the operating performance of the BFE-GSHP. In assessing the performance of ejectors, a critical metric is the mass entrainment ratio (MER), the ratio of the mass flow rate of the refrigerant fluid to that of the drive fluid. Ejector entrainment ratio is a direct indication of its performance as indicated by the formulas below relating the entrainment ratio, ω, to the cyclic COP [13]. As shown below, the COP is directly proportional to: (a) ω, which is a strong function of the momentum versus pressure exchange by the ejector and the ratio of fluid molecular masses, and (b) the ratio of enthalpy change at the evaporator and boiler, a strong function of the ratio between the phase change enthalpies of the refrigerant and drive fluids respectively. The COP is expressed as follows:

$$COP = \frac{Q_{S,Evap}}{Q_{P,Boil}} = \frac{Q_{P,Cond} - Q_{P,Boil}}{Q_{P,Boil}} \frac{Q_{S,Evap}}{Q_{S,Evap} - Q_{S,Cond}} \quad (1)$$

COP of a *second law ideal* BFE-GSHP can be estimated by replacing the heat flux ratios in Equation (1) with the ratio of temperatures (linear temperature scale defined on the basis of Carnot cycle).

$$COP = \frac{T_{Cond} - T_{Boil}}{T_{Boil}} \frac{T_{Evap}}{T_{Evap} - T_{Cond}} = \frac{1 - T_{Cond}/T_{Boil}}{T_{Cond}/T_{Evap} - 1} \quad (2)$$

Equation (2) shows that the smaller the difference between the evaporator and condenser temperatures, the higher the Carnot cycle efficiency. Increasing the temperature of the boiler also increases the COP, however, one must also consider the influence of such an increase on the specific heat of the primary fluid. Indeed, the specific heat of the primary fluid increases with the boiler temperature, and this is not favorable for the COP. For an actual BFE-GSHP, the COP of Equation (2) can be rearranged as follows:

$$COP = \frac{Q_{evaporator}}{Q_{boiler}+W_{pump}} = \omega \frac{(h_{s,out}-h_{s,in})_{evap}}{(h_{p,out}-h_{p,in})_{boiler}+\frac{(P_{p,out}-P_{p,in})_{pump}}{\rho_{avg,in\,out}}} \quad (3)$$

If the enthalpy change occurring between the inlets and exits of the evaporator, boiler and condenser is approximated by the enthalpies of vaporization, equation (3) can be rearranged as follows.

$$COP = \omega \frac{Hv_{Evap}+\overline{Cp_1}(T_{Cond}-T_{Evap})}{Hv_{Boil}+\overline{Cp_2}(T_{Boil}-T_{Cond})} = \omega\, f_h \quad (4)$$

Where Hv_{Evap} and Hv_{Boil} are the enthalpy of vaporization at the evaporator (secondary fluid) and the boiler (primary fluid) temperature, respectively; $\overline{Cp_1}$ and $\overline{Cp_1}$ are the average specific heat capacity of the primary fluid (between boiler and condenser) and the secondary fluid (between evaporator and condenser); and ω is the mass entrainment ratio. The parameter f_h is introduced to represent the term:

$$\frac{Hv_{Evap}+\overline{Cp_1}(T_{Cond}-T_{Evap})}{Hv_{Boil}+\overline{Cp_2}(T_{Boil}-T_{Cond})} \quad (5)$$

While the Cycle COP presented relate to ejector and fluid performance, this is distinct from BFE GSHP "system COP," which also considers the impact of the work inputs of the GSHP system components on the refrigeration cycle COP. Future developments will incorporate the impact of parasitic loads (pumps, fans, controls, etc.) and thermal losses throughout the system (combustion losses, standby losses, etc.).

2.1.2 Building Energy Modeling

In the near term, experimentally-derived performance curves of the BFE system will be used to model the energy and utility cost savings of the BFE-GSHP at various locations in different climate zones using EnergyPlus. These results will be compared with those of three baseline HVAC systems which represent high efficiency and minimum efficiency gas options. These baseline systems are (1) minimum efficiency central AC (SEER 13.0) and forced-air gas furnace (AFUE 0.78), (2) Energy Star air source heat pump (SEER 15 and HSPF 8.2) and (3) Energy Star ground source heat pump (cooling EER 17.1 and heating COP 3.6).

The team will then recommend system modifications and potential market entry for the BFE-GSHP based on the comparison.

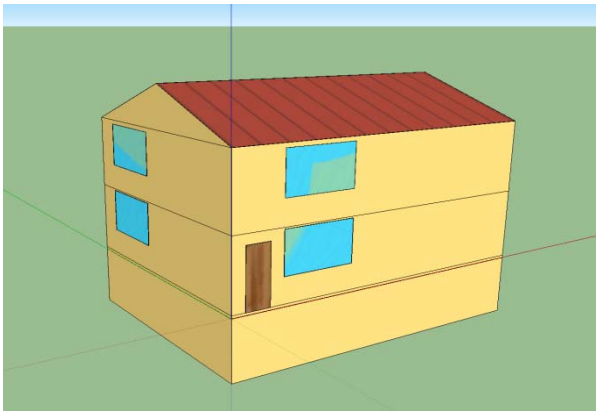


Figure 8: Reference Simulation House

The baseline simulation has been developed in four major U.S. cities, namely Chicago IL, Boston MA, Nashville TN, Colorado Springs CO. The building in this study, which is the residential prototype used by the U.S. DOE's Building Energy Codes Program, is a detached single-family residential house with heated basement, built to the International Energy Conservation Code (IECC) 2009. According to the prototype, energy is consumed in the building for heating, cooling, interior and exterior lighting, and interior equipment such as refrigerator and dishwasher, fans and water system. This study will focus only on HVAC energy use, thus the energy used for HVAC per conditioned area is shown in Figure 9 for the three baseline cases. The standard electric GSHP base case consumes less site energy as compared with the other two systems. The BFE-GSHP system to be modeled in the study is driven by natural gas, and when it is compared to the electric GSHP might have a savings of both site and primary energy.

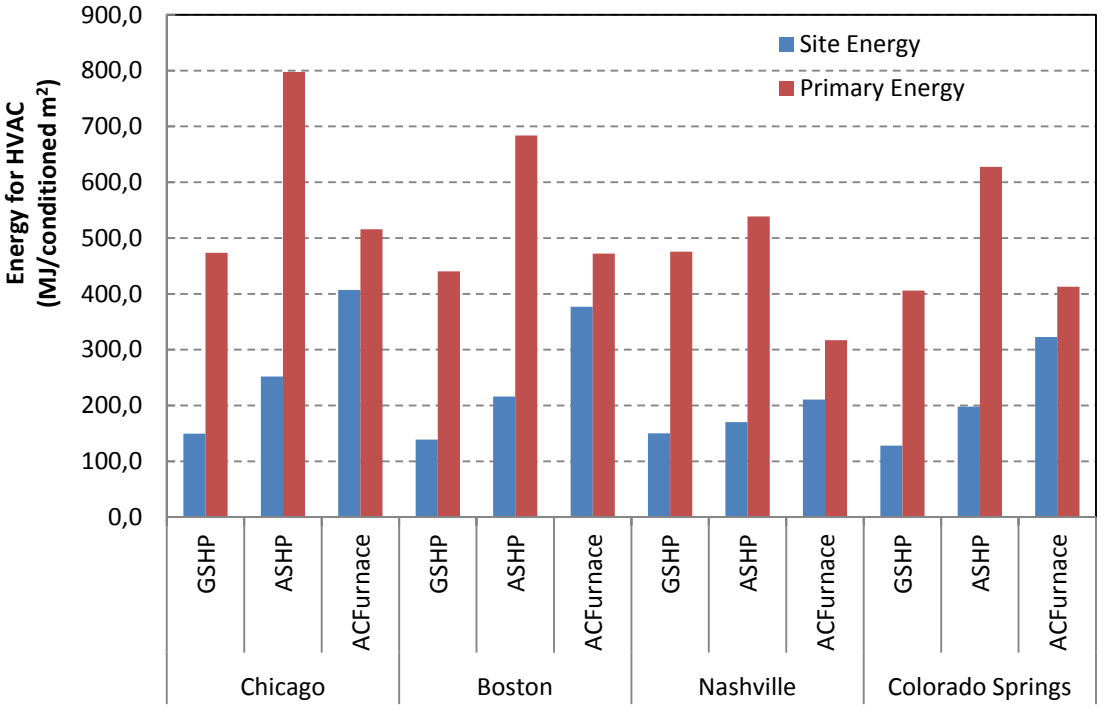


Figure 9: Comparison of Energy Consumed by HVAC for three baseline systems (Site to primary energy conversion factor is 3.167 and 1.084 for electricity and natural gas, respectively)

3. Conclusion

Development of the thermally-driven Binary Fluid Ejector Ground Source Heat Pump (BFE-GSHP) targeting residential and small-commercial applications is in early stages. However, initial modeling results indicate that, configured as a natural gas-fired system, the BFE-

GSHP may offer primary energy and operational cost savings versus baseline heating and cooling systems, as well as electric GSHPs in most regions. As a thermally-driven compression process, system efficiency is inversely proportional to compression ratio, therefore an application with a steadier and smaller temperature lift ($T_{cond} – T_{evap}$) is better suited for a BFE system. Therefore BFE heat pumps are more suitable for use with ground source heat exchangers than air source heat exchangers for residential HVAC applications.

As discussed, the BFE technology is based on traditional steam-jet ejectors, a type of fluidic compressor driven by an external thermal source. This 100 year old technology is simple, scalable, and reliable, but suffers from poor thermal efficiency. That limitation, however, has been overcome by: (a) using a distinct binary fluid pair, allowing the drive fluid and the refrigerant to each be selected or engineered to be optimal for their separate functions, (b) using an ejector nozzle design which leverages fluid dynamic techniques employed in aerospace applications to enhance the entrainment and pressure ratio of the refrigerant, and (c) optimization of the ejector geometry specific to processing a binary fluid, versus the geometry used in standard ejectors to process a single fluid. Preliminary estimates of BFE performance, initially as applied towards distillation and more recently HVAC, indicate the potential for a non-incremental annual efficiency improvement from standard HVAC equipment. The authors outline future development of the BFE-GSHP concept and BFE design along with its evaluation using building energy modeling software tools.

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