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Analysis of a Data Center Using Liquid-Liquid CO_2 Heat Pump for Simultaneous Cooling and Heating

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ABSTRACT

Liquid–liquid CO_2 heat pump systems are a promising technology for commercial building applications, which require simultaneous heating and cooling. This paper presents the investigation of a data center on the Purdue University, West Lafayette campus. The data center located in the Department of Mathematics is the most energy intensive data center on campus. The cooling load of the data center is approximately 750 kW/hour. The heating season in West Lafayette is 7 to 8 months and the heating load of the buildings is very high during the coldest months. The heating load of the Mathematics building can go to as high as 600 kW/hour during the coldest days of the year. To suffice this simultaneous cooling and heating demand, a liquid-liquid CO_2 heat pump is proposed. Presently, the cooling load of the data center is met by eight electrically driven and four steam-driven chillers and the heating load is satisfied by two coal fired and two natural gas boilers. Simulations are performed to compare the proposed CO_2 heat pump system with the present system. The assessment shows noteworthy fuel savings and reduction in the CO_2 emissions with the system working with a coefficient of performance (COP) of 6.19. If the CO_2 heat pump system is installed, 574.92m^3/day of natural gas and 751.68 kg/day of coal could be saved on a cold day. The system has the potential to reduce CO_2 emissions by 2980.76 kg/day.

1. INTRODUCTION

All electrical equipment produce heat, which must be removed to prevent the equipment temperature from rising to certain level. CPUs should always work under ~65C, GPUs under ~75C and Memory chips under ~85C (Geet, 2014). As the power densities have been considerably increasing, much more heat is generated by the servers and cooling is becoming more challenging. Figure 1 shows about 50% of consumed total electrical power is spent on cooling equipment in data centers. Therefore in recent years, incorporation of a cooling system with greater efficiency has become a key focus in the data center industry, as operators seek to cost-effective solutions for growing demand. There are several ways to provide cooling to a data center. Recently, the use of direct water at the rack level is being employed for Information Technology Equipment Cooling system. The main reason is the ability of water and refrigerant to carry larger amount of heat per unit volume or mass.

In this paper, a data center using water as a coolant on the Purdue campus has been considered for analysis. Among the 40 data centers on the Purdue campus, the data center located in Mathematics department (MATH data center) is the most energy intensive data center. Various efforts are being made to decrease its energy utilization. The MATH data center has an average hourly power consumption of 1.1-1.5 MW. It also accomodates Conte, the nation's fastest university-owned supercomputer, developed in collaboration with HP, Intel, and Mellanox. With such powerful supercomputers in place, cooling these super computers consumes significant amount of energy.

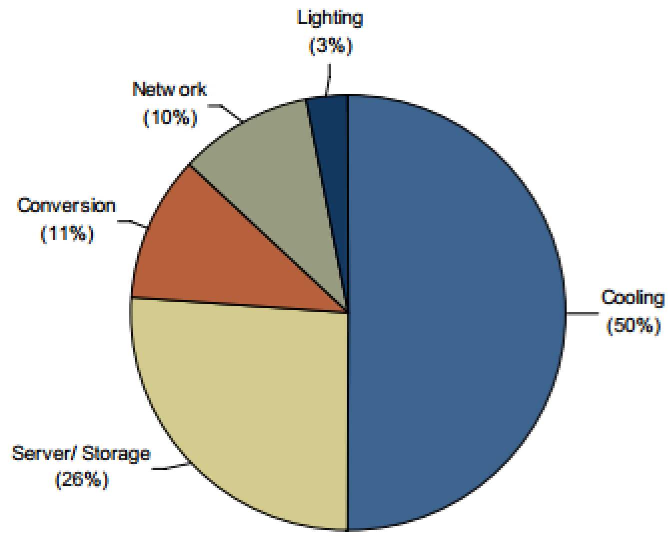


Figure 1: Typical break down of energy consumption in a Data Center (Info-tech Research Group, 2007)

The hourly energy required to cool this data center is approximately 700 kW. The chilled water to meet the cooling demand is provided by the Wade Utility Plant located on the campus. There are 14 external Cooling distribution Units (CDU) located in the MATH data center which circulate water in 101 rear door cooling units. Figure 2 shows a schematic diagram describing the functioning of the Cooling Distribution Units (CDU) distributing water to the rear door units. All the piping is done under the floor. The maximum chilled water capacity is about 65 kg/s but the actual hourly usage is only about 30 kg/s.

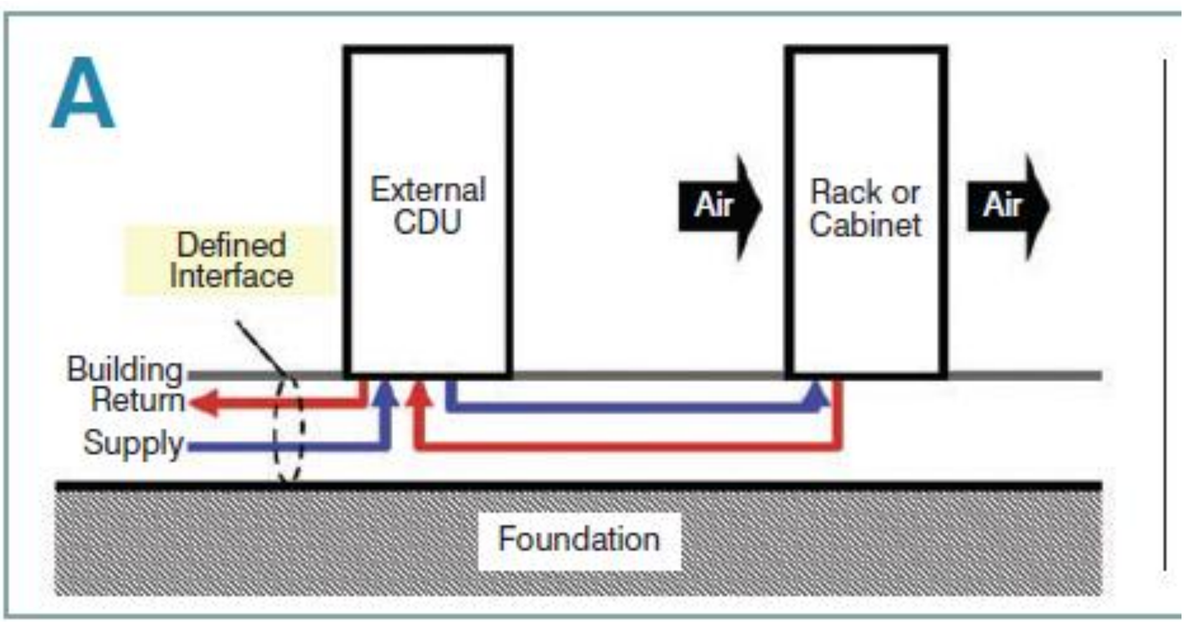
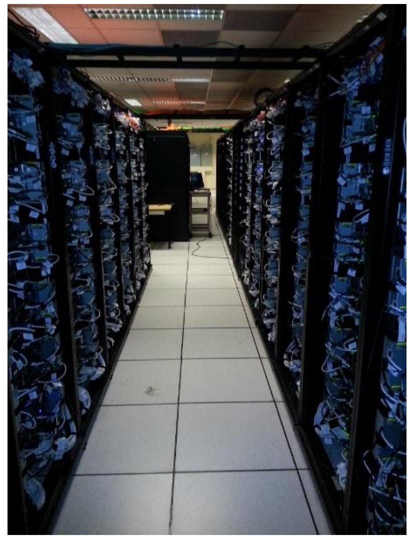


Figure 2: Schematic diagram showing the external CDU system (Steinbrecher, 2011)

Figure 3 shows the actual pictures of the MATH data center

a)



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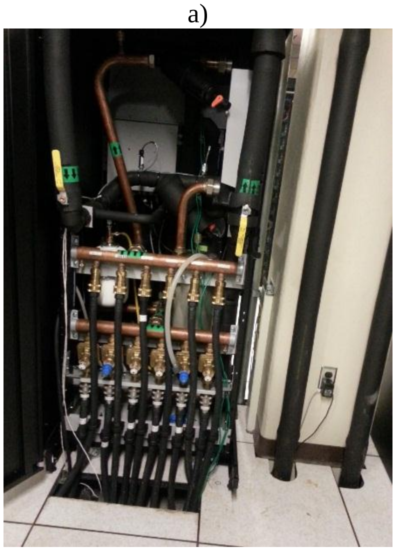

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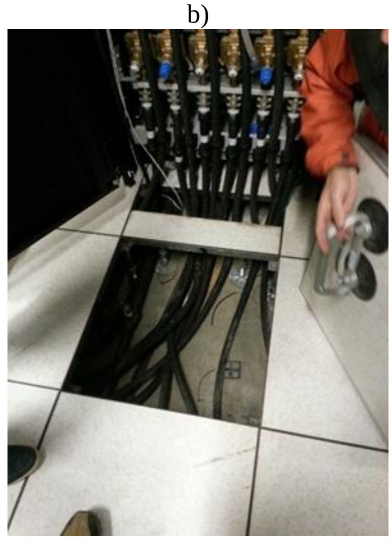

d)

Figure 3(a) Conte Super computer **(b)** Rows of Server racks in the MATH data center
(c) Cooling Distribution Units (CDU) **(d)** Underfloor piping distributing chilled water from CDU to the rear door

Table 1 gives the ASHRAE standards for facility supply water temperature. The present cooling system comes under Class W1/W2, which means it is cooled using chillers and cooling tower. The system is designed as per the standards to provide chilled water supply temperature of 43°F which well between the ASHRAE range.

Table 1: ASHRAE Liquid Cooled Guidelines (Steinbrecher, 2011)

Liquid Cooling Classes	Typical Infrastructure Design		Facility Supply Water Temperature
	Main Heat Rejection Equipment	Supplemental Cooling Equipment	
W1	Chiller/Cooling Tower	Water-side Economizer (With Drycooler or Cooling Tower)	35.6°F to 62.6°F
W2			35.6°F to 80.6°F
W3	Cooling Tower	Chiller	35.6°F to 89.6°F
W4	Water-side Economizer (With Drycooler or Cooling Tower)	N/A	35.6°F to 113°F
W5	Building Heating System	Cooling Tower	>113°F

Substantial amount of heat is absorbed during the cooling of data centers. Instead of wasting the rejected heat, heat pumps can be used to utilize waste heat to provide hot water for applications such as district heating, domestic hot water heating, etc. A sytem using the waste heat to run a liquid-liquid CO_2 heat pump system is proposed in this paper.

Phasing out of CFC's led to significant decrease in the depletion of ozone layer. Ever since the phasing out of HCFC's began as discussed in Montreal Protocol (Buxton, 1988), researchers have been trying to look at HFC's as a possible alternative. But in recent times, HFC's have also come under scrutiny due to their high GWP (Global Warming Potential) and some countries are considering their phase out. Because of its physical and thermal properties, CO_2 became a good alternative refrigerant for refrigeration system. It is non-flammable, non- toxic, inexpensive and widely available with a GWP of 1. Sarkar (2006) has studied CO_2 heat pump cycles for simultaneous cooling and heating loads in detail. Stene (2005) proposed CO_2 heat pumps for residential applications. The author tested a 6.5 kW prototype CO_2 heat pump under three different modes: space heating only, Domestic Hot Water (DHW) heating only, and simultaneous heating and DHW heating and documented the results. CO_2 heat pumps have also found application in automotive air conditioning and Environmental Control Units as they are compact. In this paper, a simulation model is developed to show advantages of simultaneous heating and cooling using liquid-liquid, CO_2 heat pump in MATH data center on Purdue campus.

The transcritical CO_2 refrigeration cycle shows a good performance in heat pump applications; however, the system performance is significantly influenced by ambient temperature (Sarkar et al., 2010), which limits the applications in domestic cooling through year round usage (Byrne et al., 2009). Blarke et al. (2012) shows how a 'thermal battery' system has the capability of simultaneous cooling and heating, which may reduce the seasonal temperature affects. Houbak-Jensen et al. (2013) present an analytical model, which can be used for the study of dynamics of the system involving simultaneous supply of heating and cooling buildings. This model includes the dynamics of the gas cooler, evaporator, and the thermal storages while the compressor and the expansion valve are considered quasi-static. The authors have shown the importance of sizing thermal storages in designing a system for a real time application. Recognizing the importance of hot and cold thermal storage, the simulation model discussed by the authors will be extended as a part of the future work so that it can be applied to data centers.

2. CASE STUDY-DATA CENTER

2.1 Existing System to meet the heating and cooling loads

To study the application of the CO_2 heat pumps in data center, the simultaneous cooling (MATH data center cooling) and heating (MATH building heating) loads are studied. There are 40 data centers on campus and the MATH data center is the most energy intensive data center. The average power consumption of this data center is 1.1-1.5 MW whereas the cooling load is in the range of 700-800 kW. There are 101 cooling door units (CDU) which are installed to meet the cooling load. The chilled water is provided to the MATH data center at 7^{o}C at a rate of approximately 32 kg/s. For heating the MATH building, steam is provided at 180^{o}C. Figure 4 shows the MATH building data center cooling load and the complete building heating load for Jan 2nd, 2014. The data center cooling load is constant throughout the day and is represented by a blue line in Figure 4. The heating load increases gradually in the morning, becomes constant and then decreases along the day as shown using a red line. Figure 5 shows the energy flow diagram of the present system. There are two coal fired and two natural gas fired boilers at the Wade Utility plant. The steam provided by these boilers is used to meet heating demand for the MATH building. The cooling is provided by eight electric driven and four steam driven chillers. The total cooling load for the data center is 17.87 MJ/s and heating load in a day is 13.3 MJ/s. The fuel energy consumed for heating is 15.64MJ/s and for cooling is 4.88 MJ/s where as the total fuel energy consumed by the existing system is 20.52 MJ/s.

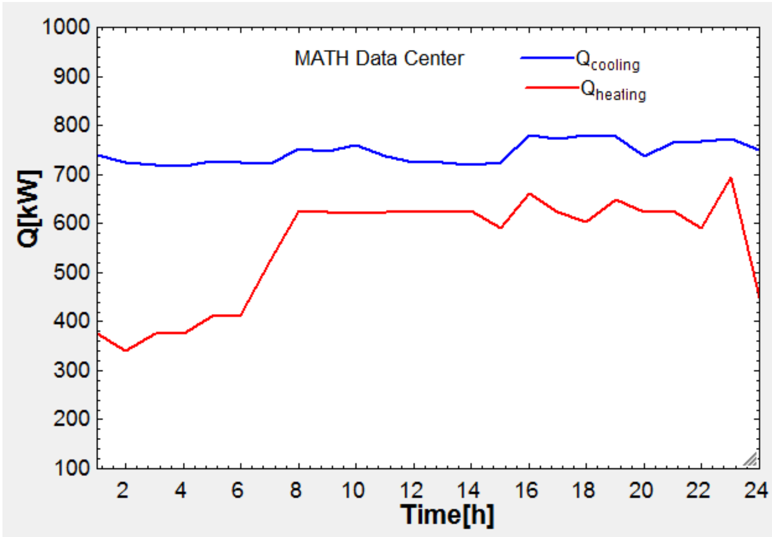

Figure 4: Variation of heating load of MATH building and cooling load of MATH data center

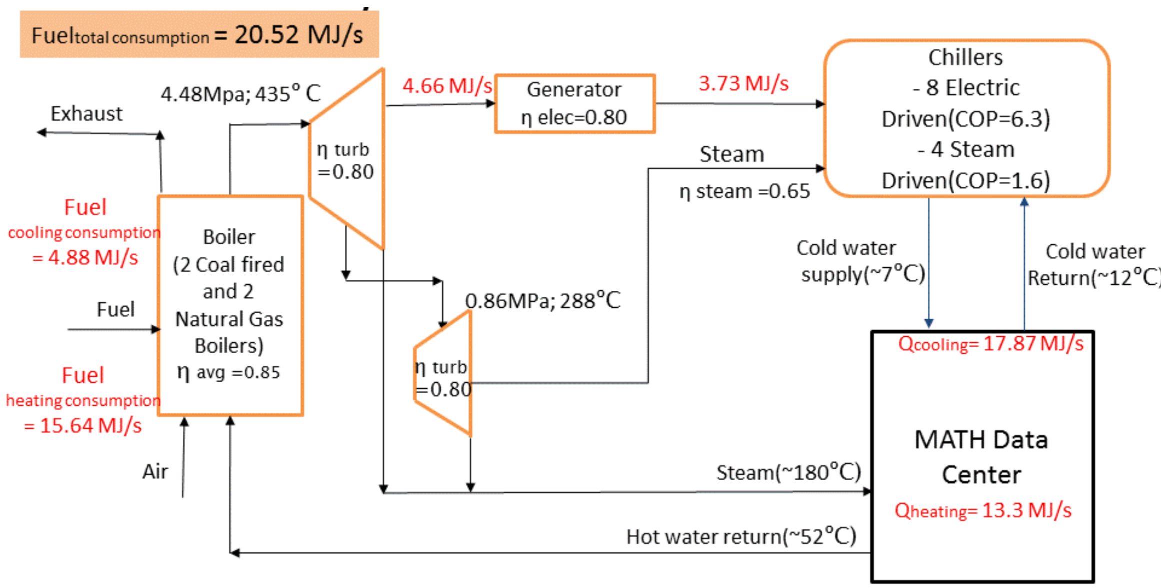

Figure 5: Energy flow diagram of the present system

2.2 Proposed CO_2 heat pump system

A CO_2 heat pump system is proposed for the data center application which is simulated using Engineering Equations Solver (EES). A high pressure compressor is used to achieve the required temperatures. The system is designed for optimum high side pressure of 7.5 MPa. A gas cooler is used to raise the temperature of water to approximately 80°C and thus, provide the required heating load of the MATH data center. As the hot water return temperature is 52°C, the high temperature gas cooler has to be designed for CO_2 outlet temperature of approximately 57°C. This leads to low system COPs. Hence, the system incorporates an air cooled heat exchanger to further cool the temperature of the CO_2 refrigerant before it passes through the expansion valve. The proposed system is designed for a particular cold day so that the cold ambient temperature of approximately 0°C can be used to the system's advantage. An evaporator is used to reduce the temperature of water from 12 °C to 7°C. A schematic of this heat pump system represented in Figure 6. It is proposed to install this system in place of the existing chillers.

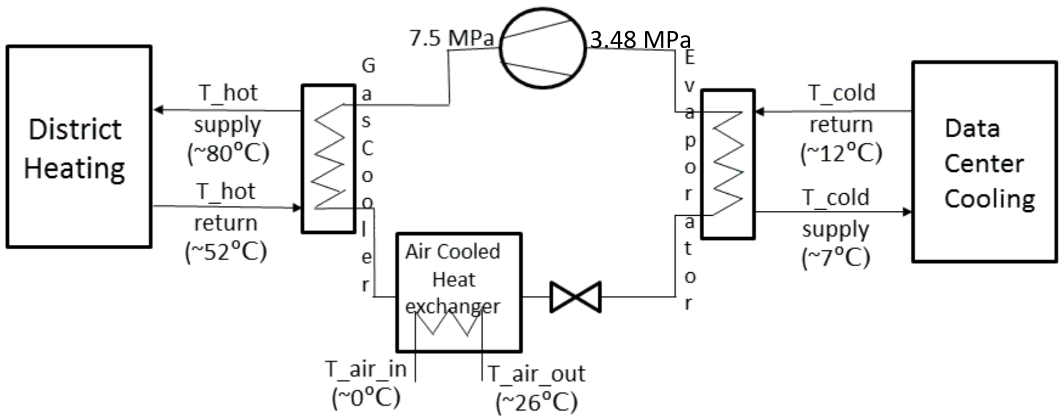

Figure 6: Schematic diagram of the proposed heat pump system providing simultaneous heating and cooling

Figure 7 shows the fuel energy consumed by the proposed heat pump system represented by an energy flow diagram. The power consumed by the CO_2 compressor is 4.614 MJ/s-day. The fuel energy consumed by the proposed system, 8.48MJ/s is less than half of what is consumed by the existing system.

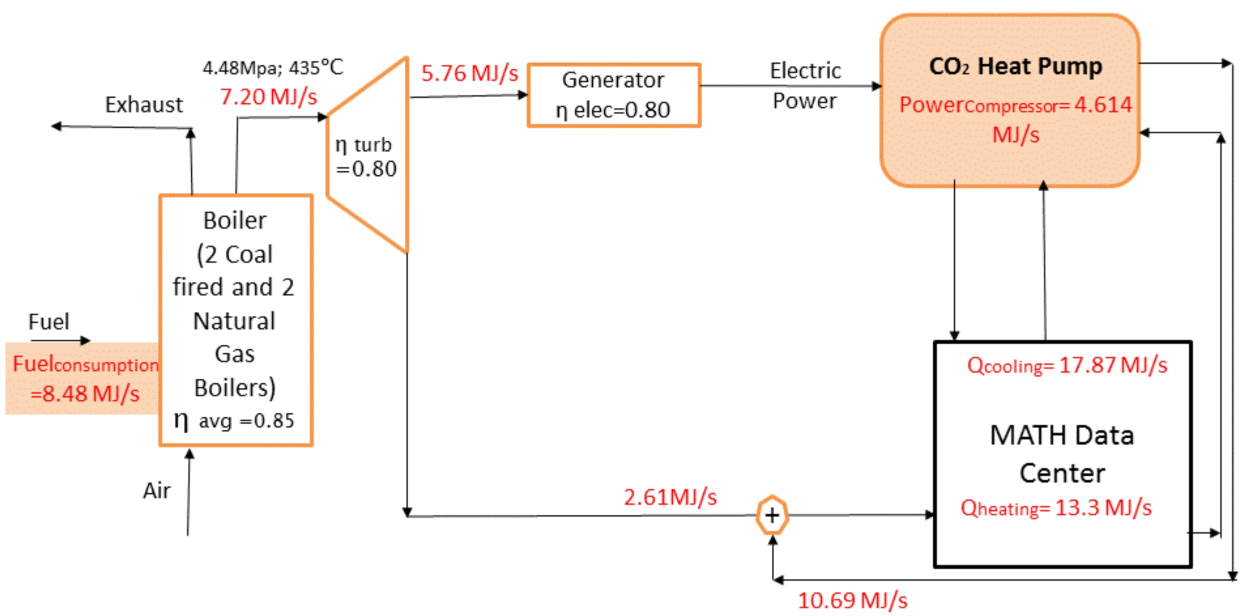

Figure 7: Energy flow diagram with the chillers replaced with proposed CO_2 heat pump system

2.3 Comparison of the existing system with the proposed system

Table 2 shows the comparison between the existing system and the proposed system in terms of Coefficient of Performance, total fuel energy consumed, total coal and natural gas consumed and amount of CO_2 emissions for January 2nd, 2014. The savings in energy is calculated using equation (1).

$$Energy\ Savings = \frac{Q_{cooling}+Q_{heating}-Q_{simultaneous}}{Q_{cooling}+Q_{heating}} \quad (1)$$

The results shown in Table 2 assume the calorific value of coal to be 20.41 MJ/kg (Mastalerz, 2004), and the heating value of natural gas to be 37.74 MJ/m^3. This yields natural gas savings of approximately 574.92 m^3/day and coal savings of approximately 751.68 kg/day. The CO_2 emission factor for coal is considered to be 87.3 kg/GJ (Mastalerz,

2004) and for natural gas to be 50.29 kg/GJ. The CO_2 emissions due to natural gas in the existing system is calculated to be 1859kg/day and because of coal is calculated to be 3222 kg/day. Whereas with the proposed system the CO_2 emissions due to natural gas in the existing system is calculated to be merely 768.24 kg/day and because of coal is calculated to be 1332 kg/day. This totals to reduction in CO_2 emissions of about 2980.76 kg/day. There are 8 electric driven and 4 steam driven chillers, hence, a weighted average is used in the calculations to determine the COP. As there are 2 natural gas and 2 coal fired boilers, they are assumed to have equal load distribution.

Table 2: Comparison between existing and proposed system

	Existing System	**Proposed System**	**Savings**
$COP_{cooling}$	4.733	3.873	-
$COP_{heating}$	- (heating directly provided by boilers)	2.317	-
Total Fuel Energy(MW/day)	20.52	8.48	12.04
Total natural gas(m^3/day)	979.56	404.64	574.92
Total coal consumed(kg/day)	1255.68	504	751.68
Total CO_2 emissions(kg/day)	(1859+3222)=5081	(768.24+1332)=2100.24	2980.76

The table shows that energy savings of approximately 59.6% can be achieved on a cold winter day.

4. CONCLUSIONS

The proposed application of a CO_2 heat pump system providing simultaneous heating and cooling shows significant savings of approximately 59.6% on a cold winter day. On a particular day January 2^{nd}, 2014, the simulated system shows heating coefficient of performance of 2.317 and a cooling coefficient of performance of 3.873, resulting in total COP of 6.19. On a cold day, 12.04 MW of energy, 574.92 m^3 of natural gas and 751.68 kg of coal could be saved if this system is installed. This system has the potential to reduce CO_2 emissions by 2980.76 kg/day.

5. FURTHER WORK

The data center simulation discussed in this paper is calculated only for a single winter day. Annual energy calculations varying with the ambient temperature will be conducted. Though the cooling demand of the data center does not vary, the heating demand is highly time dependent. Hence, finding optimum thermal storage capacity optimization for reasonable response of time-dependent demands at minimum electricity becomes important. A dynamic model with thermal storages referenced in the paper is being improved and its prediction will be validated using experimental results. The model will then be used to simulate other existing data centers on the Purdue campus.

NOMENCLATURE

$Q_{coooling}$	Energy required to provide data center cooling (current system)
$Q_{heating}$	Energy required to provide heating (current system)
$S_{imultaneous}$	Energy required to run the proposed CO_2 compressor

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