PAPER ID: 1139
DOI: 10.18462/iir.gl.2020.1139

Heat pump/chiller system for centralized kitchens in India

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ABSTRACT

A heat pump unit using CO_2 as working fluid is designed to meet not only a part of the heating demand in the centralised kitchen at The Akshaya Patra Foundation, Bengaluru, India, but also the entire cooling demand to replace the existing HCFC units for AC. The proposed heat pump system generates hot water at ~90ºC which is stored in hot water storage tanks for use in the cooking cauldrons. Moreover, the existing space cooling systems are replaced by a centralised cooling system which circulates chilled water. In order to handle the fluctuation in cold and hot water demand, thermal storage systems are proposed. This concept offers substantial reductions in GHG emissions from the cooling system (approximately 60%). Furthermore, for the overall system (cooking process and space cooling) the reduction in energy demand, energy cost and GHG emissions are all above 30%.

Keywords: Heat Pump, Carbon Dioxide, Thermal storage, GHG.

1. INTRODUCTION

The Akshaya Patra Foundation is a not-for-profit organization headquartered in Bengaluru, India. The organization strives to eliminate classroom hunger by implementing the Mid-Day Meal Scheme in government schools and government-aided schools. Alongside, Akshaya Patra also aims at countering malnutrition and supporting the right to education of socio-economically disadvantaged children. Today, Akshaya Patra is the world's largest (not-for-profit run) Mid-Day Meal Programme operating around 50 centralized kitchens supplying wholesome food every school day to over 1.8 million children at more than 16,000 schools in 12 different states across India [www.akshayapatra.org]. The implementation model of these semi-automated kitchens can be efficiently scaled and replicated and has attracted curious visitors from around the world. The Akshaya Patra Mid-day Meal Programme uses large quantities of primary energy for its day-to-day cooking. The organization strongly believes that energy sustainability is of great importance to overall sustainability given the pervasiveness of energy use, its importance in economic development and living standards, and its impact on the environment. The "Akshaya Patra Heat Pump Project" is one of the energy sustainability initiatives taken by the organization.

Implementation of CO_2 heat pump technology has been identified as having the potential to play a major role in reducing the energy consumption of the kitchens. Heat pump technology achieves increased heating efficiencies by over three to four times compared to conventional oil and gas boilers. In the course of identifying sustainable and energy efficient approaches, pilot air source heat pumps have been implemented in a few kitchens. However, a water source heat pump can deliver higher-performance heating and simultaneous provide useful cooling capacity. A heat pump based on CO_2 as the refrigerant can efficiently produce both hot water and chilled water at suitable temperatures for the cooking process and space cooling respectively. Together with hot- and cold-water storage, it can cover parts of the heating demand in the kitchen and the total cooling demand for the AC system and food storage rooms in the building complex.

2. KITCHEN DESCRIPTION AND ENERGY DEMAND

In the existing system, the heating system supplies heat to the cooking process at the centralized kitchen in Bengaluru and cooling system for space cooling (AC) in the associated building complex. All kitchens of

Akshaya Patra follow a standard process for preparing mid-day meals. This process is charted out to ensure hygiene and quality of the cooked meal and to adhere to the food safety standards.

Figure 1. Internal view of Akshaya Patra's kitchen area.

Fig. 1 shows the internal view of Akshaya Patra's kitchen area. The kitchen is equipped with cauldrons, trolleys, rice chutes, dal/sambar tanks, cutting boards, knives, etc. All equipment is sterilized using steam before the cooking process begins early in the morning. Each cauldron has a capacity to cook at least 500 litres of rice and up to 3000 litres of dal. Steam, supplied from boilers, is injected into the bottom of the cauldrons, raising the water temperature. Critical Control Points (CCPs) like cooking temperature are checked and recorded at periodic intervals to ensure the right quality of the meal. The cooked food is packed in steam sterilized steel vessels before loaded on transport vehicles, also sterilized before the loading process. The Bengaluru kitchen supplies mid-meals to 551 schools, on 27 routes covering a radius of 50 km [1].

2.1. Heating Demand

In the kitchen, steam boilers are installed, all fueled with HSD (High Speed Diesel). The boiler generates steam at 150°C at 5 bar (gauge pressure). The steam available at the individual cooking cauldrons is around 130°C. Through steam injection, the water in the cauldrons is heated up from around 24°C to about 120°C. With a heat pump implementation, the water could be heated up to 90°C before introducing the steam into the cauldrons, thus reducing the required amount of steam. The boilers operate 6 hours per day (4 am to 10 am), consuming on average 960 litre HSD fuel. Table 1 shows the current heating demand and fuel consumption in the kitchen.

Table 1: Current heating demand and fuel consumption in the kitchen.

Unit (Boiler)	Maximum output	Steam production	Fuel consumption	
	kW	kg/h	l/h	l/day
1	530	850	40	240
4 (Total)	21200	3400	160	960

2.2. Cooling Demand

The AC cooling systems in the complex area housing the kitchen consists of mostly split AC units (7-8 years old) and a few window AC units (very old and not working). Both are using the ozone depleting refrigerant HCFC-22, which also has a relatively high global warming potential (GWP). Table 2 shows the current cooling capacity, the number of AC units and power consumption in the kitchen.

Table 2: Current cooling capacity, number of AC units and power consumption in the kitchen.

Unit (Split)	Cooling capacity	Power Consumption	COP	Refrigerant	No of units
	kW	kWh		HCFC-22	
1.5 TR	5.3	2	2.6	1.3	10
2.0 TR	7.0	2.7	2.6	1.7	1
17 TR (Total)	60	22.7	2.6	3.0	11

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2.3. Kitchen Load Profile

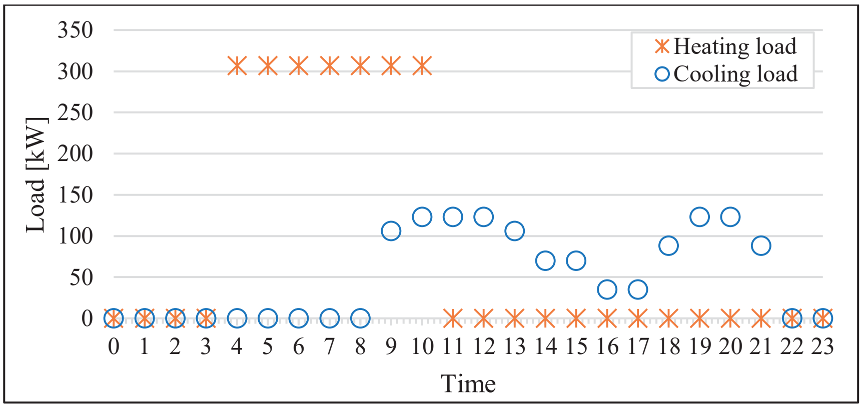

Figure 2. The heating and cooling load profile for a typical day

Fig. 2 shows the heating and cooling load profile for a typical day. The heating load represents only the demand for producing 90°C water, which is to be delivered by the heat pump, i.e., the remaining steam demand for the cooking process is not included. Hot water is required for 6 hours, from 4 am to 10 am, at a constant load of 307 kW, resulting in a hot water energy demand of 1830 kWh for a typical day. The space cooling demand occurs from around 8 am to 10 pm. The maximum cooling load is 123 kW, and the total cooling demand during a typical day is 1213 kWh.

3. CO_2 HEAT PUMP SYSTEM

The maximum heating capacity in the simulated heat pump system is ~141 kW. For the same, the heat pump operation time would be 13 h/day, which could cover the daily hot water demand of 1830 kWh. During the preliminary stage, the simulation of the heat pump system is carried out using the simulation platform Modelica/Dymola. Table 3 shows the parametric operation of the simulated CO_2 heat pump system.

Table 3: Parametric operation of the simulated CO_2 heat pump system.

Hot water production (24ºC to 90ºC)		**Cold water production (12ºC to 5ºC)**	
Maximum hot water demand [kW]	306	Maximum cold water demand [kW]	123
Hours of heating demand [h/day]	6	Hours of cooling demand [h/day]	13
Daily heating demand [kWh]	1836	Daily cooling demand [kWh]	1213
Average daily heating demand [kW]	306	Average daily cooling demand [kW]	93
HEAT PUMP			
Heating capacity [kW]	141	Cooling capacity [kW]	102
Operating hours [h/day]	13	Operating hours [h/day]	13
Daily heating capacity [kWh]	1833	Daily cooling capacity [kWh]	1326
Hot water production [l/min]	33	Cold water production [l/min]	12.5
Heating COP	3.62	Cooling COP	2.62
Combined (heating + cooling) COP	6.25	Combined (heating + cooling) COP	6.25
Power consumption [kWh/day]	22.6	Power consumption [kWh/day]	16.3

Fig. 3 shows the CO_2 heat pump system simulated for the kitchen. The reason why the specific cooling COP is not improved in the new system is the large temperature lift for the heat pump compared to the existing AC units operating only between indoor and outdoor temperatures. According to simulations of the system the heating COP is 3.62, resulting in total electricity consumption of 39 kW and a cooling capacity of 102 kW. However, since the heat pump covers both a cooling and heating demand, it is the total (combined) COP of 6.25 that is relevant and shows the high efficiency of the proposed heat pump chiller device. This high efficiency is achieved through design features like a multi-ejector and a double-stage (i.e., two-temperature-level) evaporation process. An operation time of 13 h results in a daily cold-water production of 1326 kWh, which is 113 kW more than the average daily demand. If this surplus cold is not required, it must be removed in order to not fill up the cold storage. This can simply be done by installing an outdoor unit or an additional cooling fan coil, in which the surplus cold is rejected to the outside air or other areas where cold air might be useful.

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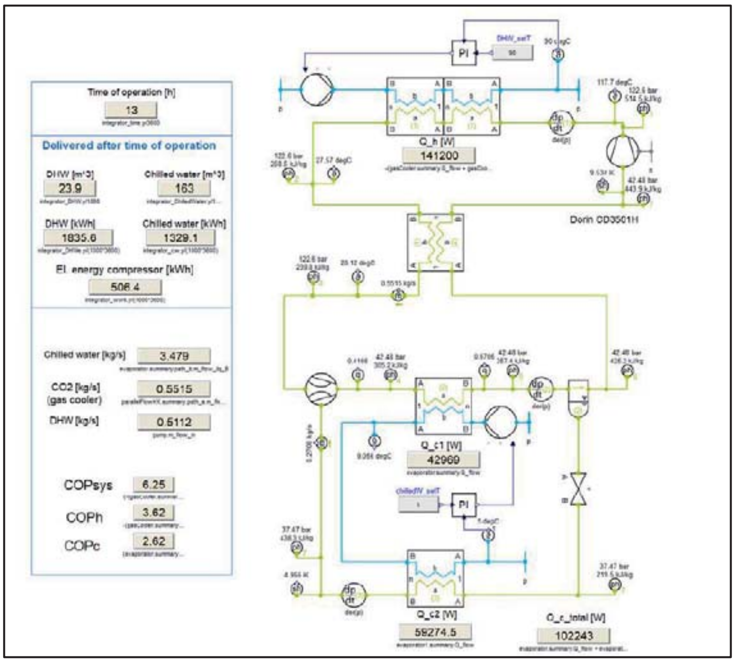

Figure 3. CO_2 heat pump system simulated for kitchen.

3.1. Thermal Storage

It is observed that there is a mismatch between the hot water and cold-water demand, both in time and load (Fig. 5). Thermal energy storage (TES), such as hot and cold-water buffer tanks, is an established concept for balancing the mismatch in demand and supply of heating and/or cooling. It also allows designing the production unit (heat pump in this case) for a lower maximum output.

3.1.1. Heat pump operation: 4 AM to 5 PM

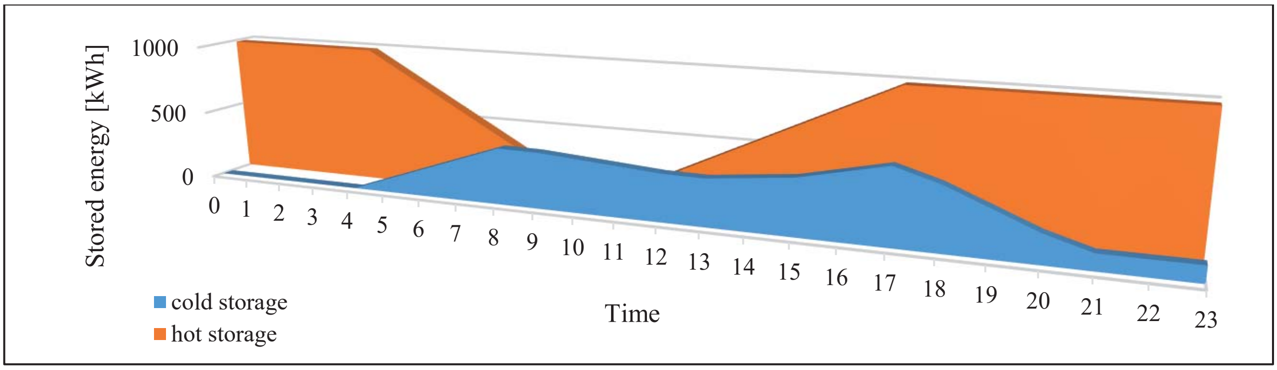

Figure 4. The usage of cold and hot storage energy throughout the day.

The heat pump starts operating early morning when the cooking process begins and continues to operate for a period of 7 hours after the cooking process is completed. Hot storage is filled up with 141 kWh each hour, which then is stored during the non-operating period of 11 h. When the cooking process begins, the heat pump starts again and together with the stored heat, the heating demand of 307kW can be supplied for 6 hours. The required amount of stored heat energy is around 1000 kWh, corresponding to a storage volume of 14 m^3. The cooling demand occurs during a longer period and is more variating, being both higher and lower than the 102 kW delivered by the heat pump. This means that there are more continuous charge and discharge of the cold-water storage tank. Fig. 4 shows the usage of cold and hot storage energy throughout the day. It is observed that, for an operation period of 13 h, a surplus cold of 113 kWh is produced, which is assumed to simply be "removed" at the end of the day. The maximum amount of cold energy that must be stored is 535 kWh, corresponding to a cold-water volume of about 65 m^3. Since the temperature difference of the cold water is only 7°C, compared to 66°C for the hot water, the storage volume for a certain amount of energy becomes much larger.

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4. ENERGY AND ENVIRONMENTAL BENEFITS

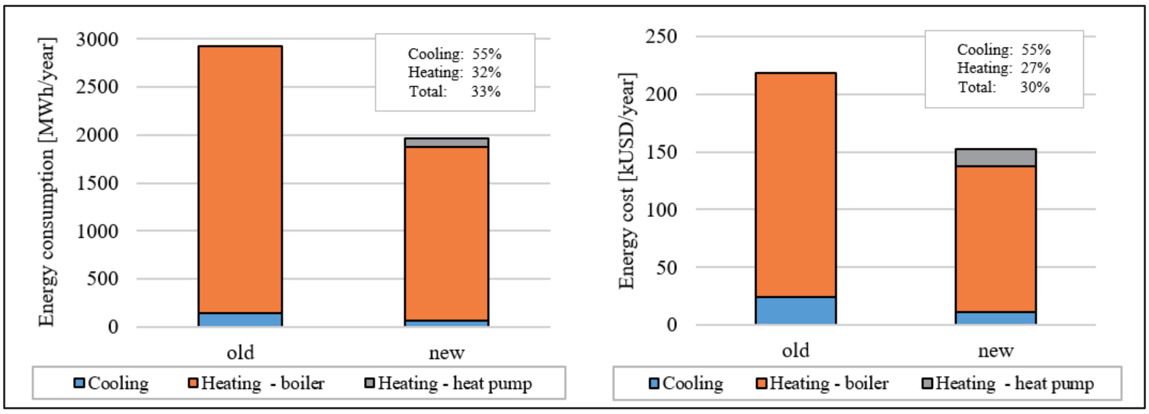

Figure 5(a): The energy consumption for the old heating and cooling system as compared to the new proposed solution, Figure 5(b): Energy savings in terms of energy cost.

Fig. 5(a) shows the energy consumption for the old heating and cooling systems as compared to the newly proposed solution. The reduction in energy use for the cooling system is 55%, while the reduction in heating energy consumption is "only" 32%, due to the remaining steam demand for raising the water temperature and keep it boiling in the cauldron during cooking. For the total system (cooking process and space cooling), the reduced energy consumption is 33%. Fig. 5(b) shows the energy savings in terms of energy cost. The energy savings are converted to savings in energy cost, using an electricity cost (for industry) of 0.17 USD/kWh and an HSD fuel price of 0.98 USD/litre, corresponding to around 0.1 USD/kWh. The heat pump reduces HSD fuel consumption, but since the electricity price is higher, the cost savings for the heating system is slightly lower than the reduced energy consumption. Still, the total savings are 30%.

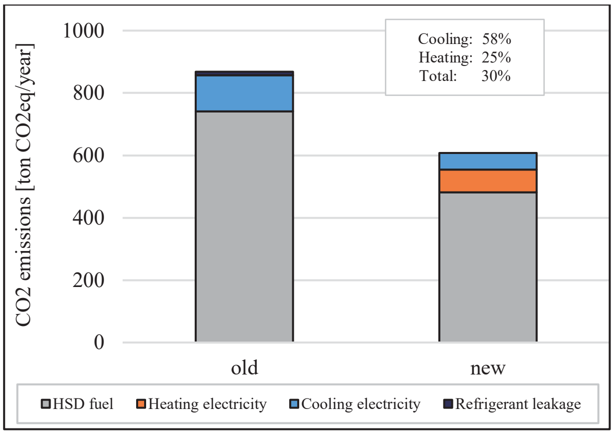

Figure 6. The reduction in greenhouse gas emissions.

In Fig. 6, the total GHG emission from the heating and cooling system is compared for the old existing system and new solution, showing the total reduction in GHG emission for the cooling system is 60% (with an assumed refrigerant leakage rate of 30%).

5. PROPOSED SYSTEM DESIGN

Fig. 7 shows the proposed design of CO_2 heat pump/chiller system. The unit is designed to provide a constant heating and cooling capacity towards dedicated storage devices of the kitchen. Therefore, on the heating side, the water cooled gas cooler recovers heat by heating up water to around 80°C, applied for cooking. At the same time, cooling is provided to deliver chilled water via two evaporators (medium and low-temperature) arranged in series on the water side. Moreover, the system is equipped with an internal heat exchanger (IHX) to provide additional benefits in the overall system performance and to secure a certain superheat upstream of the compressor. To partially recover the throttling losses in the system, a two-phase multiejector is used with the potential to adjust the capacity, however, mainly to maintain the required high side pressure. The receiver/separator is used to introduce pure liquid and vapor phases towards the evaporators and compressor

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respectively, which eventually unloads the compression work partly during the operation as expansion work is recovered by the ejector. The basics of the proposed control system are as follows:

- Two-phase multiejector block controls system high-side pressure by adjusting the total number of ejector cartridges in operation (ON/OFF operation of individual ejectors of various capacities)
- Metering valves in both water loops (hot and cold) regulate the mass flow rate in order to maintain the requested outlet temperature (Hot water setpoint: around 80-90ºC and Chilled water setpoint: 12-7ºC).
- LT-evaporator feeding: electronic expansion valve maintains a constant pressure difference of 3-5 bar between evaporator and receiver.
- MT-evaporator feeding: by gravity forces (no expansion device), self-circulation
- Safety features:
    - If suction pressure is below 38 bar, compressor stops (for more than 30 sec) to avoid freezing of water in the pipes and HXs.
    - System shut down: when thermal reservoir tank (hot and cold) is fully charged. Compressor gets stop signal (circuit open's, responding to the level switch inside the storage tank).
    - Charging port and safety valve (LP) at receiver (90 bar rating with horizontal design)
    - System stand still temperature requirement: 40°C.
    - Oil return from low pressure side: timers control the opening time of oil return valves.

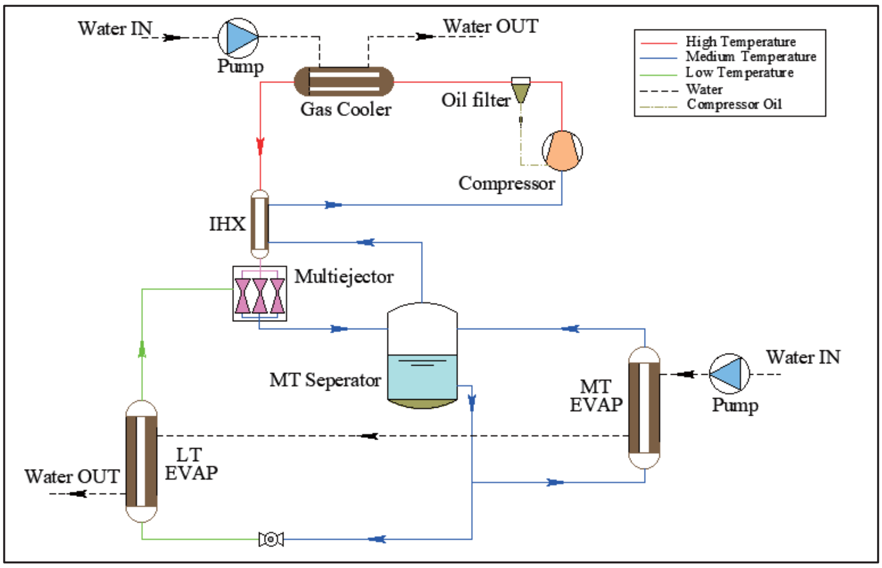

Figure 7. Proposed design of the CO_2 heat pump/chiller system.

6. CONCLUSIONS

From the evaluation of the environmental benefits of implementing the proposed solution, the following indicative conclusions were drawn;

- Replacing the HCFC air-conditioning units with the CO_2 heat pump offers more than 50% reduction in power consumption for the space cooling system and almost 60% reduction in GHG emissions.
- By implementing the heat pump for producing hot water to the cooking process reduces the kitchens total energy consumption (HSD fuel) of more than 30% and the CO_2 emissions with 25%. Steam boilers must still be applied for raising the water temperature to boiling point and keep it boiling during cooking.
- For the total system (cooking process and space cooling) the reduction in energy demand, energy cost and GHG emissions are all above 30%.
- A CO_2 heat pump producing simultaneously hot and cold water is an extremely efficient way of supplying both heating and cooling needs, especially if they occur at the same time. However, by installing hot and cold-water storage tanks, the mismatch in both load and time can be balanced.

ACKNOWLEDGEMENTS

The work presented is part of an ongoing Indo-Norwegian cooperation funded by the Ministry of Foreign Affair of Norway (MFA) and will be part of the INDEE+ project and Department of Science and Technology (DST) under the project SPARC. Moreover, author(s) would like to appreciate the support provided by Team of The Akshaya Patra Foundation.

http://dx.doi.org/10.18462/iir.gl.2020.1139