ENERGY EFFICIENCY IN HVAC SYSTEM: CASE STUDY OF A HOSPITAL BUILDING COMPARING PREDICTED AND ACTUAL PERFORMANCE AND SHOWING IMPROVEMENTS THROUGH PERFORMANCE MONITORING

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ABSTRACT

It is well known that the HVAC (Heating, Ventilating and Air Conditioning) system accounts for the maximum energy consumption in most of the commercial buildings. In hospitals, HVAC system becomes even more important as the cooling (temperature and relative humidity setpoints) and ventilation (fresh air change rates) requirements are more stringent as compared to other commercial buildings. Hence, greater potential exists to save energy by incorporating energy efficiency measures in HVAC system.

The paper presents case study of a 350-bed multi-specialty hospital building in warm-humid climate (Pune), focusing on the HVAC system performance estimated through simulation at design stage, measured data post occupancy and impact of few measures identified during the monitoring. Energy efficiency measures include building envelope measures to reduce cooling load such as AAC block external wall, insulated roof and double-glazed window. HVAC system measures included optimum sizing of chiller, selection of energy efficient chillers with good part load performance, enthalpy recovery wheels for fresh air, use of condenser for reheating in air AHUs and heat pumps for water heating. Annual electricity consumption shows around half of the electricity is consumed by HVAC system and the EPI of the hospital is 136 kWh/m^2.y, which is very close to the predicted performance (130 kWh/m^2.y). The hospital gets a 4-star rating under BEE star rating for hospitals. During energy monitoring, operational improvements (increasing chilled water generation temperature, reducing condenser water temperature, change in heat pump control, etc.) in HVAC system were tried and later implemented; which resulted in further ~10% energy saving.

Keywords—hospital, energy efficiency, HVAC system, performance monitoring *(keywords)*

INTRODUCTION

In India, buildings contributed to ~33% of the total electricity consumption of 1130 TWh in 2017-18 (Energy Statistics, 2019). Projection done by NITI Aayog under different scenarios shows that the electricity consumption for the residential sector is expected to increase 6-13 times from 2012-2047 and 7-11 times for the commercial sector in the same time frame (IESS, 2047).

Energy performance index (EPI) (kWh/m^2.y) of commercial buildings is much higher as compared to residential buildings and also have a greater potential to save energy per unit area. Study conducted under ECO-III project showed that the average EPI of Indian multi-specialty hospitals was 378 kWh/m^2.y with a consumption of 13,890 kWh/bed.year (Kumar et al., 2010).

Heating, ventilating and air-conditioning (HVAC) system accounts for the maximum energy consumption in most of the commercial buildings. In hospitals, HVAC system becomes even more important as the cooling (temperature and relative humidity setpoints) and ventilation (fresh air change rates) requirements are more stringent as compared to other commercial buildings. The share of HVAC energy consumption in hospital buildings varies between 30-65% (ECO-III, 2009).

While there are many case studies available on energy efficient commercial buildings based on the energy simulations only; very few studies goes a step beyond and provide the simulated energy performance with the actual performance through detailed energy monitoring.

This paper presents case study of a hospital building, keeping a focus on HVAC system, and details out:

- Energy efficiency measures adopted in the building.
- Results of the building energy simulation during the building design.
- Comparison of predicted and actual energy performance
- Results of the performance monitoring of HVAC system

About the building

This hospital is a 350 bed multi-speciality tertiary care hospital (**Figure 1**). The building is situated in Pune which falls under warm-humid climate.

Figure 1: Hospital Building, Pune

Key details of the buildings are:

- Built-up area: 26,580 m^2 (excluding parking and service floor: ~9,500 m^2)
- Number of floors: 3 underground floors, 9 overground floors + 1 service floor
- Types of spaces: Technical areas like MRI, ICUs, Cath lab, OTs; patient indoor rooms and recovery rooms; restaurants, emergency rooms, etc.

Project timeline & key steps

- A design workshop for energy-efficient design with key project team members was organised at the design stage in February 2014. This workshop resulted in identification & selection of energy efficiency measures (EEMs) as well as building energy simulation to quantify energy savings.
- Construction of the building was completed in December 2016 and the hospital is functional since then. During the construction period, EEM proposals were further detailed out and the selection of HVAC system was done.
- Energy monitoring of HVAC system was done during November 2018 and May 2019 while the energy bills for 12 months (May 2018 to April 2019) were analysed.

Energy efficiency measures implemented

To improve the energy performance and daylight in the building, following measures were implemented:

- Roof insulation: 150 mm of RCC roof slab was insulated with 100 mm extruded polystyrene (XPS) which gives a U-value of 0.31 W/m^2.K.
- External wall: External walls were made of 150 mm AAC block with plaster on both sides, resulting in a U-value of 0.9 W/m^2.K.
- Glazing: The project team emphasised the importance of daylight in faster recovery of patients and clear glass was selected. However, double glazed units were selected to have a lower U-value of 2.8 W/m^2.K.
- Chiller sizing: Use of dynamic energy simulation software for chiller plant sizing instead of simplified calculation based on static design conditions. Installed chiller capacity is 560 TR (280 x 3 nos., 2 working + 1 standby).
- Chiller selection: High efficiency chiller with a COP of 5.92 with a very good part load performance (NPLV: 0.367), was selected.
- Enthalpy recovery wheels, with 75% effectiveness for both latent and sensible heat recovery, were integrated in the fresh air AHUs.
- Condenser water is used for reheating (refer **Figure 10**) the air in AHUs for maintaining the relative humidity. The backup hot water is provided by a heat pump system with a COP of 2.81.
- Free cooling: Patient floors have the provision of free cooling, which means if the the ouside air is suitable for space cooling, it can directly be supplied without passing through the cooling coil.

The system sizing calculation were done using HAP software and energy simulation of the building was carried out using DesignBuilder software to quantify the benefits of the integration of EEMs. The key results of the energy simulation were:

- Reduction in cooling system size: The cooling system size was reduced from 600 TR (before the design workshop) to 424 TR (after the integration of EEMs), which is a 29% reduction in the cooling system size (**Figure 2**).

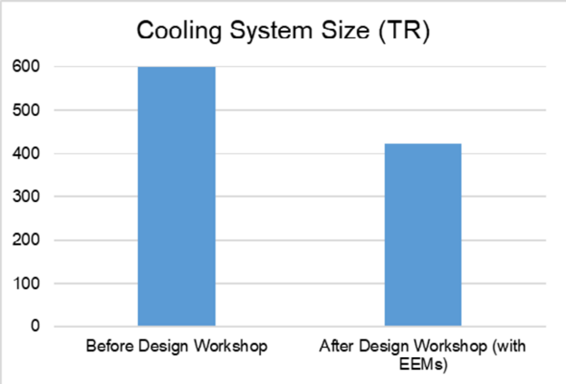


Figure 2: Reduction in cooling system size with EEMs

- Reduction in energy consumption: The energy performance index (EPI) was reduced from 154 kWh/m^2.y to 130 kWh/m^2.y (16% reduction) after considering EEMs in energy simulation (**Figure 3**).

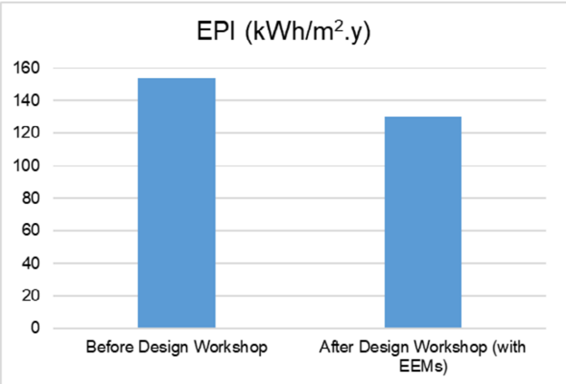


Figure 3: Reduction in EPI with EEMs

HVAC system monitoring

Energy monitoring for this building was focussed on HVAC system (**Figure 10**) as it contributes most (~60% as per calculations done during design workshop) to the total energy consumption. HVAC system monitoring was done during November 2018 and May 2019 while the energy bills for 12 months (May 2018 to April 2019) were collected. The monitoring included assessment of the HVAC system operation practice followed by the facility team and its impact on energy consumption. The utility equipments with significant impact on energy include chillers, cooling towers, chilled water and cooling water pumps, treated fresh air units and heat pumps. Performance of these utility equipments were evaluated during the study and compared with the design parameter and prevailing norms.

This paper discusses energy consumption pattern of the building and analyses the performance of the systems. It also tries to assess the impacts of trials or modifications carried on the systems.

For performance evaluation purpose, the following portable instruments were used, as mentioned in **Table 1**.

Table 1: List of instruments used during monitoring

S. NO	NAME OF INSTRUMENTS	MAKE	MEASUREMENT
1	Single CT power meter	MECO	Snapshot power measurement
2	Three CT Power Analyzer	Oracle	Power Data Logging
3	Three CT Power Analyzer	Krykard	Power Data Logging
4	Swing Psychrometer	JRM	DBT & WBT
5	Lux meter	TES 1332 A	Lux level
6	Surface contact type temperature sensor	Libratherm	Measurement of surface temperature on condenser water header
7	Ambient temperature + %RH sensor	Libratherm	Ambient Temperature + %RH
8	Ultrasonic Water Flow meter	GE	Data logging of Water flow through main header of condenser
9	Infrared Temperature Gun	Testo	Measurement of Envelope temperature

Key measurements done during the monitoring are listed below:

- Electrical system
  - All electrical panel meter readings on hourly basis
  - Power logging for chillers
  - Snapshot measurements of lighting and power distribution boards
  - Snapshot power measurements of cooling tower and pumps, heat pump
- Water Flow Measurements
  - Chilled water secondary flow logging
  - Cooling tower flow measurements
  - Heat pump flow measurements
- Treated Fresh Air Units
  - Power, airflow across energy recovery wheels
  - Electrical power for fans
  - Temperature and RH measurements

In addition some specific measurements were done:

- To measure the impact of reduced condenser water temperature in chiller performance
- To evaluate the combined efficiency of two VFD based chillers, when operated at part load as compared to one chiller operation in full load
- To measure the performance of cooling tower when two cooling towers were operated as compared to one cooling tower for similar cooling loads
- To measure the effectiveness of treated fresh air (TFA) unit

RESULTS AND DISCUSSIONS

Overall energy performance

The electricity consumption data for 12 months (May.18 to Apr.19), collected during the monitoring, is shown in **Figure 4**.

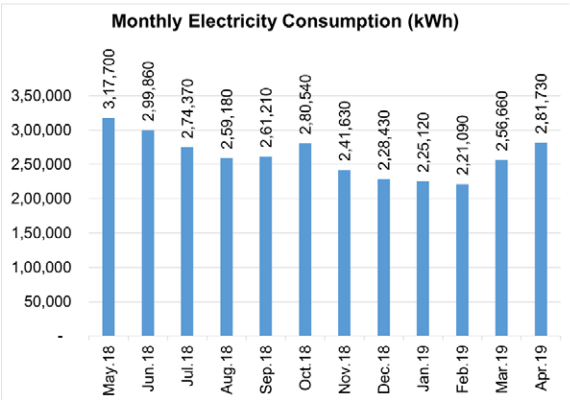
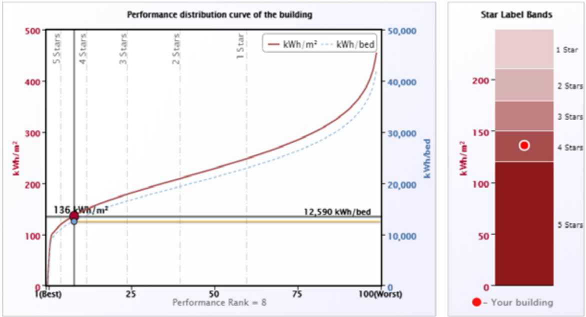


Figure 4: Actual monthly electricity consumption

During the monitoring period, two recovery floors were not operational, resulting in operational beds as 250 and the overall operational area as 2,49,000 ft^2. The annual energy consumption of this hospital was 31,47,520 kWh/y, resulting in an EPI of 136 kWh/m^2.y and 12,590 kWh/bed.y. Simulated EPI did not account for sewage treatment plant, outdoor lighting and basement ventilation; this would add ~8-10% in the EPI. Overall, simulated EPI (130 kWh/m^2.y) is in very good agreement with the actual EPI (136 kWh/m^2.y).

The energy performance of the building was evaluated under the BEE star rating of hospital using the ECObench tool, which is the energy benchmarking and rating assessment for hospitals. The results (**Figure 5**) show that this buildings qualifies for a 4-star rating.



Parameters	Measured	Benchmark
Electricity Used (kWh)	3,147,520	5,292,889
EPI (kWh/m²)	136	229
EPI (kWh/bed)	12,590	21,172
Building Performance Rank: 8		

★ ★ ★ ★

Figure 5: Results from BEE's Benchmarking & Performance Rating Tool for Hospitals

The break-up of energy consumption (**Figure 6**) shows that the HVAC system consumes 50% of the total energy consumption, and chillers contribute maximum (19%). Chiller plant hydronics mainly includes primary chilled water pump, secondary chilled water pump, cooling tower pump and cooling tower fans. Other HVAC mainly includes hot water system, cold storage and basement ventilation.

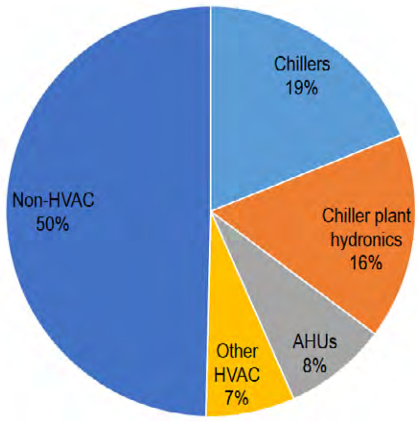


Figure 6: Break-up of energy consumption

HVAC system monitoring results

Impact of reduced condenser water temperature in chiller performance

During the winter monitoring in November 2018, it was observed that the cooling water (input to the condenser of the chiller) temperature was kept to 27-28˚C considering the reheating requirements. However, it was possible to achieve a cooling water temperature of 21-24˚C from the cooling tower. The measured data show that, with reduced water temperature, average chiller energy consumption during winter was reduced from 1646 to 1434 kWh/d, while in summer it reduced from 1972 to 1693 kWh/d

(**Figure 7**). This resulted in chiller energy saving of 13% in winter and 14% in summer.

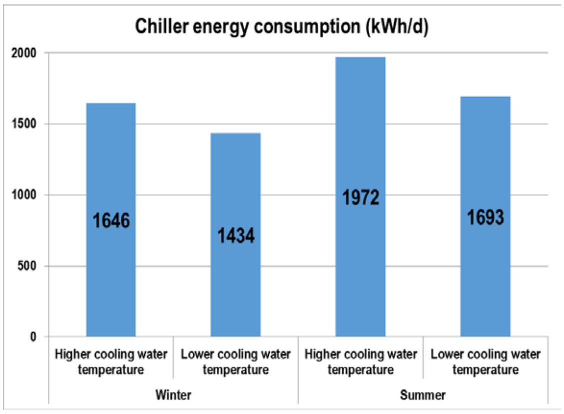


Figure 7: Impact of reduced condenser water temperature on chiller energy consumption

Chiller part load parallel operation vs single chiller full load performance

Chillers installed are equipped with VFD, thus the part-load performance of the chillers is better than full load performance. The performance comparison was done by running two chiller in part load and one chiller in full load. In Case 1, two chillers, two primary chilled water pumps, two secondary chilled water pumps, two cooling water pumps and two cooling towers were operational. In Case 2, one chiller, one primary chilled water pump, two secondary chilled water pumps, two cooling water pumps and two cooling towers were operational.

The average chiller performance measured in Case 1 was 0.41 kW/TR while in Case 2, it was 0.46 kW/TR (**Figure 8**). This shows that the chiller performance in Case 1 was 12% better as compared to Case 1.

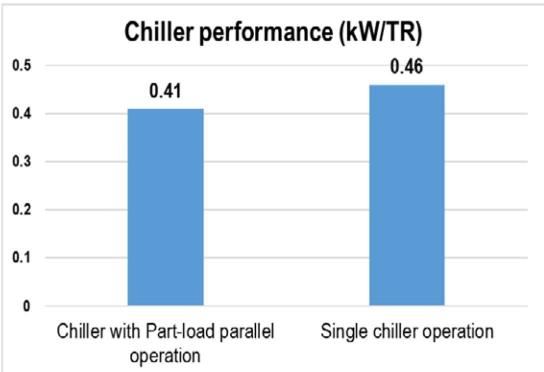


Figure 8: Chiller part load parallel operation vs single chiller full load performance

Cooling tower performance

The hospital has two cooling towers installed of capacity 349 TR each. Both the cooling towers are operated with one chiller operation or two chiller operation. The measurements were done for two cases: Case 1, when two cooling towers are operational and Case 2, when only one cooling tower was operational.

During Case 1, the heat load on cooling tower 1 and cooling tower 2 was 104 TR and 103 TR respectively, as against rated capacity of 349 TR. The key results were:

- The cooling tower approach was measured to be 1.4˚C and 2.1˚C for cooling tower 1 and cooling tower 2, respectively, while the design approach is 3˚C.
- The water-to-air ratio of the cooling tower 1 and 2 were 0.36 and 0.46 respectively, while the design vaue is 0.67.
- Effectiveness for cooling tower 1 and 2 were 71% and 61%, respectively.

During Case 2, the heat load on cooling tower was 234 TR, as against rated capacity of 349 TR. The key results were:

- The cooling tower approach was measured to be 3.7˚C and water-to-air ratio was 0.90.
- Effectiveness for cooling tower was 49%.

TFA unit performance

The facility has treated fresh air units installed for supplying fresh air. Measurements were carried out of the TFA during the study. The TFA had heat recovery wheel to cool the fresh air using the exhaust air. Chilled water was used for further cooling of the fresh air (**Figure 9**).

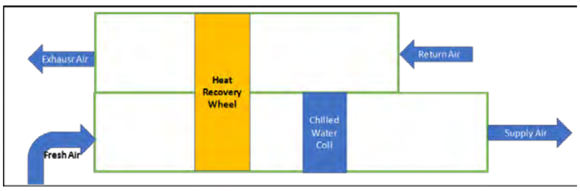


Figure 9: Schematic of TFA unit

Measurements were done to calculate the effectiveness of heat recovery wheel (HRW) installed in the TFA unit. Measured data of temperature of return air before HRW as 29.4˚C, fresh air as 33.3˚C and fresh air after HRW as 30.0˚C results in an sensible effectiveness of HRW as 85%.

Further energy saving opportunities

Presently, when only one chiller is operational, two cooling towers are operated to keep condenser water temperature low and therby chiller energy consumption. Cleaning of cooling tower fills and descaling of basin and cooling water circuit will help achieve the designed performance. Potential energy savings by this measure are 48,180 kWh/y.

For a significant duration (~4500 hous), ambient temperature and humidity in Pune remains below the design conditions. This gives an opportunity to run cooling tower fans on part-load but presently, there is no VFD for cooling tower fans. Installing VFD for cooling tower fans will help optimize it's energy consumption. Potential energy savings by this measure are 49,500 kWh/y.

Cooling water pumps flow rates can also be optimized as per ambient conditions but they also do not have VFDs. Installing VFD on cooling water pumps (3 nos.) will help optmize the flowrates and reduce energy consumption. Potential energy savings by this measure are 22,500 kWh/y.

CONCLUSION

Good quality case studies based on monitored energy performance are needed for promoting energy efficiency in buildings. The paper presents case study of a hospital building at Pune and cover:

- Energy efficiency measures adopted in the building
- Results of the building energy simulation during the building design
- Methodology and results of the HVAC system performance monitoring
- Results of specific measures for HVAC system and identification of further energy saving opportunities

Energy efficiency measures (EEMs) for this building includes roof insulation, AAC block external walls, double glazed windows, chiller sizing using dynamic energy simulation software, high efficiency chiller with very good part load performance, enthalpy recovery wheels, condenser water for reheating and free cooling.

The actual EPI (136 kWh/m^2.y) of this building is very close to the predicted EPI (130 kWh/m^2.y). The monitoring of this building was focussed on HVAC system as it consumed maximum electricity (50% of the total) and has maximum saving potential as well. HVAC system components were monitored and their performance were compared with the design values. While some of the operational improvements were implemented during monitoring, further energy saving opportunities were identified with energy saving potential of 1,20,000 kWh/y.

There is a need to have many such case studies. This would help in motivating builders / developers and other building sector professional to adopt energy efficiency measures in their projects.

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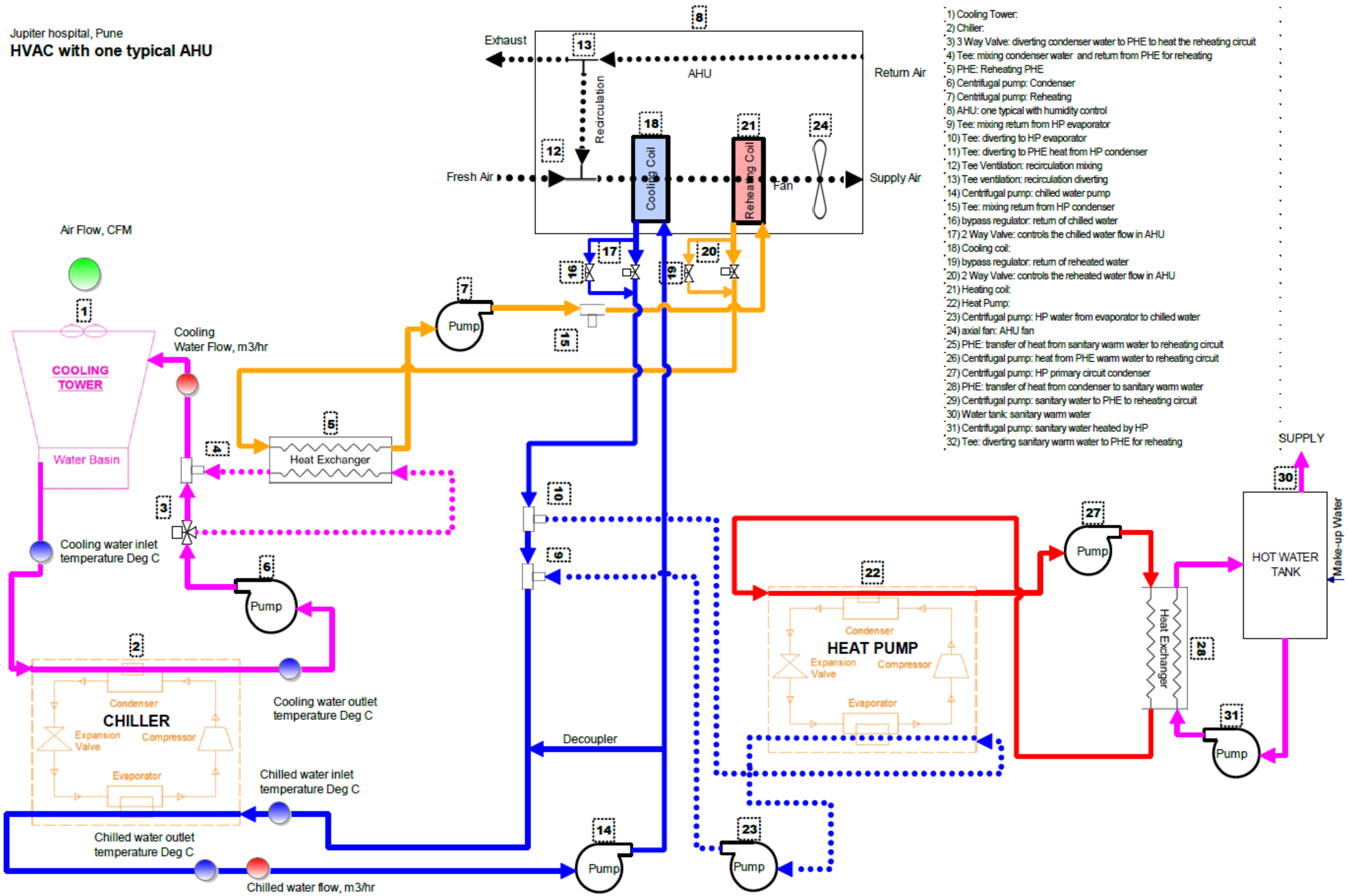

Figure 10: Simplified HVAC system schematic with one typical AHU and key measurement points

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