Comparison between the chiller air cooled with the variable refrigerant flow technology for high building air conditioning system

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Abstract. Energy efficiency is one of the emerging issues of technical and engineering studies recently. Along with the development of massively high buildings, the need of energy saving increases globally. The largest energy usage in buildings is the air conditioning system. Its energy consumption and energy efficiency are significantly affected by the type of the technology used. Therefore, this study compared the chiller air cooled with the variable refrigerant flow technology for high building’s air condition system. Technically the analysis was carried out by using the Hourly Analysis Program E-20 software as a tool to calculate the amount of electrical energy consumption at 15 floors office building’s cooling system for 6 months. Financially the comparison of both technologies was conducted by a total annual cost analysis. This study found that the electricity consumption of the chiller air cooled is lower than the variable refrigerant flow system. Besides the total cost of the chiller air cooled is more efficient than the refrigerant flow technology. The further empirical research is recommended for other different type of buildings such as hospital, factory plant, school or university, airport and so on.

1. Introduction
Along with the high urbanization growth rate around the globe, the development of massively high buildings in town is being increased significantly. Indeed, they need more energy especially electricity to make the people feel comfort and cozy to stay in the room and to support all works inside the building. The largest energy usage in buildings is the air conditioning system. Energy Efficient Air More than 50% of the total consumption comes from HVAC (heat, ventilation and air conditioning) system in building [1]. Therefore, at the time of designing a HVAC project, it is required to understand the project requirements, type of application, duty conditions and compliance to relevant standards. Nowadays, the designer has many choices for designing the HVAC system and it could be very confusing to identify a correct system for a given application.

The chilled water system is the oldest of HVAC technology has been used over decades all over the world. It is refrigeration systems used in both commercial and industrial facilities to cool fluids and/or dehumidify air. It actively absorbs heat from process water; they then transfer this heat into the air around the chiller unit. Even though the technology is outdated, the performance can still be improved. For example, coupling a direct evaporative cooler with an air-cooled condenser can achieve energy saving between 2.4% and 14.0% depending on the climatic condition [2]. By using evaporative cooled

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air condenser in hot weather conditions, the power consumption can be reduced up to 20% and the coefficient of performance can be improved around 50% [3]. The coefficient of performance (COP) of these chillers can be improved by a new condenser design, using evaporative pre-coolers and variable-speed fans [4]. There is also much opportunity for improving the operating efficiency of air-cooled multiple-chiller plants by lowering the condensing temperature at lower outdoor temperatures [5].

On the other hand, Variable refrigerant flow (VRF) systems, which were introduced in Japan more than 20 years ago, have become popular in many countries. The technology has gradually expanded its market presence and steadily gaining market share throughout the world [6]. In general, it provides more flexible controls and better thermal comfort while saving energy [7]. Some research show that the VRF systems are leading to more efficient operations than others [8-10]. VRF systems would save around 15–42% and 18–33% for HVAC site and source energy uses compared to the RTU VAV (Roof Top Unit - Volume Air Variable) systems [8]. VRF systems consumed much less air conditioning energy by up to 70% than VAV systems [10]. A study showed that the COPs determined for the VRF and central systems are 3.3 and 2.0 respectively [11]. VRF systems also have limited space requirements, particularly for the distribution system inside the building [12].

Regardless their advantage to other technologies, the VRF implementation still has some issues. The shortcoming of no outdoor air (OA) intake has not been solved thoroughly [13]. Some other research found that the VRF is not always superior to other HAVC systems. A computer simulation study results show that GSHP (Ground Source Heat Pump) system is more energy efficient than the air-source VRF system for conditioning a small office building in two selected US climates [14,15]. Some research also notice that the advantages of VRF to other systems are significantly affected by many contextual measurements such as the differences in electricity and gas use for heating sources [13], and the outdoor air temperatures [16].

Referring to the disputed studies result and along with a common confusion of engineers’ is whether to design a system for central plant with chilled water system or to use the VRF, then the comparison study between both HVAC systems is needed. This research wants to investigate the comparison between those two building Air Conditioning system in more detail and real time with the pattern of load consumption for the efficiency energy saving. So, this study wants to analyse the comparison between Chiller Air Cooler with VRF at high building in Indonesia context. It will investigate the efficiency level and economic factors in the use of electricity for HVAC include investment, operating and maintenance cost.

2. Methods
This study is conducted through a software simulation based on a 15 floors high building data in Jakarta. The operating data is gathered for 6 months consecutively. The Hourly Analysis Program (HAP) is common tool (software) to analyse HVAC systems for commercial buildings. HAP version EE-20 uses the transfer function method which is supported and aligned with ASHRAE’s rules for detailed load calculations. Using "HAP System Design Load", the program provides system design features, load estimation, and energy analysis as follows:

- HAP system design features
- HAP estimates the design of cooling and heating loads for commercial buildings in determining the size required for HVAC system components
- HAP energy analysis features
- HAP estimates the annual energy usage and energy costs for HVAC and non-HVAC in a building by simulating building operations for 8,760 hours each year.

For calculating the need of air conditioning, there are several major factors influencing the capacity of the required rooms; load from outside, partitions, ceiling, floors and load from the inside. The external load came from roof, walls and glass materials or their configuration. While internal load consist of sensible load, latent load, heat from the lamp and heat from other equipment [1]. Latent heat is related to changes in phase between liquids, gases, and solids inside the building. While sensible heat is related to changes in temperature of a gas or object with no change in phase. The operation cost
will be estimated from the result of HAP energy analysis on monthly basis. While the maintenance cost can be calculated by referring to the manual book or both technologies.

3. Data calculation

First stage to run HAP is to provide the detail data related to the cooling load of the building. The data is usually made at the beginning phase during the planning or engineering session. For the external load, generally it can be calculated by the following formula;

\[
q = U \times A \times CLTD
\]

where:
- \( q \) = Load transmission of roof/wall/glass
- \( U \) = Design heat transmission coefficients (W/m²·hr.°C)
- \( A \) = Area calculated from architecture plans (m²)
- \( CLTD \) = Cooling Load Temperature Difference (°C)

For the Partitions, Ceiling and, Floors, the cooling load is defined as follows:

\[
Q = U \times A \times TD
\]

where:
- \( Q \) = Load transmission of proof
- \( A \) = Area calculated from architecture plans (m²)
- \( U \) = Shading Coefficient
- \( TD \) = Temperature Difference

While the internal load sources came in form of heat from the occupants of the room consists of sensible and latent heat, it depends on the sex, age and level of activity carried out from the human body. [1] The sensible heat follows this equation:

\[
Q_s = No \times SHG \times CLF
\]

where:
- \( No. \) = Number of people in space
- \( SHG \) = Sensible heat gain from occupants
- \( CLF \) = Cooling load factor for people

Whereas “Latent Load” can be defined by this formulation:

\[
q_s = No \times Lat. HG
\]

where:
- \( No. \) = Number of people in space
- \( LHG \) = Latent heat gain from occupants

Heat from lamp is calculated by this equation:

\[
Q_{lamp} = INPUT \times CLF
\]

where:
- \( INPUT \) = Input rating electrical plans or lighting fixture
- \( CLF \) = Cooling Load Factor

Then heat from equipment is estimated by:

\[
Q_{equipment} = SHG \times CLF
\]

Based on all those basic equations, the amount of cooling load for the building can be estimated. For this study, the detail loading of building can be seen at table 1. Within 15 floors, the building has
12 zone load which has effect differently to the overall cooling load. The largest zone of cooling load is overhead lightning and electrical equipment. It means they provide more heat than other zones. Both people and ventilation have sensible and latent heat.

Then the second stage is to estimate the design of cooling and heating loads for commercial buildings in determining the size required for HVAC system components. Referring to the electricity consumption of the building for 6 months and its detailed cooling data, then the component cost of HVAC system can be defined by HAP. The result of HAP calculation is the monthly component cost of cooling system for both “Air cooled chiller” (figure 1 - a) and RVF (figure 2 - b).

**Table 1. Detailed cooling load of building.**

| Zone Loads                  | Details            | Sensible (W) | Latent (W) |
|-----------------------------|--------------------|--------------|-------------|
| Window & Skylight Solar Loads | 955 m2            | 155667       | -           |
| Wall Transmission           | 717 m2            | 15440        | -           |
| Window Transmission         | 386 m2            | 3870         | -           |
| Door Load                   | 955 m2            | 40281        | -           |
| Floor Transmission          | 20 m2             | 2202         | -           |
| Partitions                  | 1099 m2           | 0            | -           |
| Ceiling                     | 1346 m2           | 22113        | -           |
| Overhead Lighting           | 24 m2             | 389          | -           |
| Electric Equipment          | 156881 W          | 142624       | -           |
| People                      | 156881 W          | 150558       | -           |
| Ventilation Load            | 588               | 35559        | 35317       |
| 3451 l/s                    | 39781             | 91378        |             |

![Diagram showing cooling, pumps, lights, and electric equipment costs over months](a)
4. Result and discussion
The HAP energy analysis features provide an estimated electricity consumption for some HVAC technologies based on the detailed data of building and their monthly component cost. It is also able to estimates the annual energy usage and energy costs for HVAC and non-HVAC in a building by simulating building operations for 8,760 hours each year. Considering the limitation of the study, the utilization of operational data obtained during operating hours, from 06.00 am - 09.00 pm, is only for 6 months. The results of load analysis for both “Air Cooled Chiller” and RVF can be seen as table 2. The trend of electricity consumption for air cooling system for both technologies is consistent; from July to December increased gradually. Interestingly, even though November and December are the rainy season, the electricity consumption for air cooling system actually goes up.

Due to the chiller system is a centralized system then its investment cost is easily estimated. To achieve more flexibility and higher efficiency, some building usually combines between large and small capacity. The investment cost will include large and small chillers with AHU system, as follows:

- Chiller set 100TR IDR 1.056,900.000,-
- Chiller ser 150TR IDR 1.587,900.000,-
- AHU system IDR 486,948.160,-

Then the total investment of Air Cooled Chiller for the building is IDR 3,131,748,160,-
Table 2. Load analysis of chiller and VRF.

| Month  | Day | Chiller (kWh) | VRF (kWh) | Chiller (kWh) | VRF (kWh) |
|--------|-----|---------------|-----------|---------------|-----------|
| July   | 31  | 8104.2        | 8395.0    | 261.4         | 270.8     |
| Augustus | 31  | 8644.2        | 8890.0    | 278.8         | 286.8     |
| September | 30  | 9421.3        | 9795.0    | 314.0         | 326.5     |
| October | 31  | 9821.4        | 10095.0   | 316.8         | 325.6     |
| November | 30  | 10364.0       | 11510.0   | 345.5         | 383.7     |
| December | 31  | 11006.2       | 12915.0   | 355.0         | 416.6     |

Total Consumption Energy 57361.3 61600.0 1871.6 2010.0

Unlike the Chiller system, the VRF calculation of investment cost is little bit complex. It should consider how many units will be installed for each floor and what capacity will be suitable for each floor. Indeed, the capacity will depend on the size and cooling load of the floor or room. However, considering the similarity of floor at the building, this study only estimate the typical floor to define the need for air cooling system based on VRF. Among 15 floors, they are 4 typical floors so that investment cost of VRF is estimated as table 3. Unlike the Chiller system, the VRF calculation of investment cost is little bit complex. It should consider how many units will be installed for each floor and what capacity will be suitable for each floor. However, considering the similarity of floor at the building, this study only estimate the typical floor to define the need for air cooling system based on VRF. Among 15 floors, they are 4 typical floors so that investment cost of VRF is estimated as table 3.

Table 3. Investment cost of VRF.

| Lt | PK | BTU | Indoor Unit | Outdoor Unit |
|----|----|-----|-------------|--------------|
|    |    |     | Btu/Unit | IU/Unit | Unit Price (IDR) | Btu/Unit | OU Unit | Qty | Unit Price (IDR) | Total Price (IDR) |
| 1  | 68,0 | 61600 | 38225,0 | 19 | 214,091,137.00 | 305800 | RXQ 32AMY 14 | 2 | 156073585.00 | 312,147,170.00 |
| 3  | 74,6 | 671055 | 25809,9 | 22 | 267,327,373.00 | 335527,5 | RXQ 36AMY 14 | 2 | 176782320.00 | 353,564,640.00 |
| 5  | 114,4 | 1029490 | 44760,4 | 22 | 661,807,493.00 | 514745 | RXQ 58AMY 14 | 2 | 284712036.00 | 569,424,072.00 |
| 9  | 39,1 | 351725 | 23448,3 | 15 | 161,861,368.00 | 1758625 | RXQ 20AMY 14 | 2 | 97989320.00 | 195,978,640.00 |
| 15 | 23,6 | 212300 | 26537,5 | 8 | 92,737,146.00 | 106150 | RXQ 12AY 14 | 2 | 60975200.00 | 121,950,400.00 |
| Total | 1,397,824,517.00 | 1,553,064,922.00 | 2,950,889,439.00 |

Then based on the table 2, the operating cost of both technologies can be estimated. For calculating the operational cost, the total cooling load from July to December (6 months) is equal to energy consumption of electricity (kWh). Referring to the tariff of electricity for commercial (1 kWh = IDR 1.035) then the operating cost for air cooling system can be calculated at table 4.

Table 4. Operational cost.

| Technology | Total Cooling load (BTU) | Consumption Energy (kWh) | Operating Cost (IDR) |
|------------|--------------------------|--------------------------|---------------------|
| VRF        | 210.187.945              | 61.600                   | 63.756.000          |
| Chiller    | 195.724.901              | 57.361                   | 59.368.946          |

The maintenance cost can be easily calculated based on the instruction manual book for both technologies. The result can be seen at table 5.
Table 5. Maintenance cost.

| Tech     | Activity                        | Freq./year | Capacity | Unit Price (IDR) | Total (IDR) |
|----------|---------------------------------|------------|----------|-----------------|-------------|
| VRF      | Cleaning, checking and Inspection | 4          | 86       | 150.000         | 12.900.000  |
| Chiller  | Routine Services                | 1          | 250      | 25.000          | 6.250.000   |

Combining table 3, 4 and 5, then a significant comparison between Chiller cooling system and VRF can be concluded at table 6. It shows that Chiller system is more economical than the VRF one (the total annual cost of Chiller is IDR 250,257,981 and the VRF is IDR 337,137,963). In addition, the electricity consumption of Chiller is only IDR 2.291/kWh, while the VRF is IDR 2.737/kWh. It means the efficiency of the Chiller is 7.4% higher compared to the VRF system and financially the Chiller cooling system is 35% more efficient than the VRF one.

Table 6. Financial and efficiency of chiller and VRF.

| No  | Comparison                        | Chiller          | VRF             |
|-----|-----------------------------------|------------------|-----------------|
| 1   | Investment Cost (IDR)             | 3.131.748.160    | 2.850.889.438   |
| 2   | Life time (years)                 | 25               | 15              |
| 3   | Operation Cost (IDR)              | 118.737.891      | 127.512.000     |
| 4   | Maintenance Cost (IDR)            | 6.250.000        | 12.900.000      |
| 5   | Total Annual Cost (IDR)           | 250.257.817      | 337.137.963     |
| 6   | Electricity consumption (kWh/year)| 114.723          | 123.200         |
| 7   | Electricity consumption (IDR/kWh) | 2.181            | 2.737           |

5. Conclusion

Based on the results of the analysis, in terms of electrical energy consumption from the two cooling systems, the percentage values obtained for both Chiller and VRF. Using a simulation model, this study found that the VRF cooling system consumes energy electricity is greater than the Chiller one. Actually, the investment cost of Chiller requires a large cost, but in terms of life time Chiller can last up to 25 years while the VRF is only 15 years. Due to simpler configuration, the chiller system maintenance cost is also lower than the VRF system. Therefore, in terms of the cost of, using a Chiller system has a lower annual cost than the VRF system. This study does not support some previous research which put the VRF is superior than other air cooling technologies include the chiller system. However, the study is limited only for the simulation model, then an empirical study is highly recommended to ensure which the best air cooling technology for high buildings. The further empirical research is also recommended for other different type of buildings such as hospital, factory plant, school or university, airport and so on.

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