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Indoor Air Quality Improvement Effectiveness of Air-side Economizer using Air Quality Index

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Abstract

The object of this paper is to find a relationship between Indoor Air Quality (IAQ) and air-side economizer. When air-side economizer is operated, all outdoor air come into the space. However, if outdoor air quality exceeds IAQ standard, occupants will feel uncomfortable and even have a chance to develop following diseases: cardiac disorder, respiratory disease, etc. This paper supposes a method that reduces contaminants coming into the space when air-side economizer is operated. The main idea is to adopt Air Quality Index (AQI) as a constraint condition. AQI is determined by the most adverse influence factor to air quality among PM_{10}, $PM_{2.5}$, Ozone, Nitrogen dioxide and Sulfur dioxide. AQI from zero to fifty indicate good state and from fifty-one to one-hundred indicate moderate state. For example, if AQI exceeds certain level of harming human being, air-side economizer stops operation in spite of good temperature and humidity condition for air-side economizer operation. Simulation was developed using Energy Plus, Open Studio and Excel programs. This study selected two big cities: Seoul, South Korea and Shanghai, China. Simulation results of Shanghai showed $PM_{2.5}$ concentration over 75 $\mu g/m^3$ (China's grade II 24 average $PM_{2.5}$ standard) was about 1028 hours/year and 879 hours/year when operating differential enthalpy economizer and differential enthalpy economizer restricted AQI respectively. HVAC energy consumption increased about 2.10% when operating differential enthalpy economizer restricted AQI. It was found that $PM_{2.5}$ concentration over 75 $\mu g/m^3$ period was reduced by 2.83% when operating differential enthalpy economizer restricted AQI.

Keywords – Air-side Economizer; Indoor Air Quality; Air Quailty Index; HVAC Energy

1. Introduction

Air pollution is generally known as one of the main factors causing adverse effect on human being. This is because air contaminants have properties which are potential toxic, carcinogenic, inflammatory and allergenic (Maroni et al., 1995). Annesi-Maesano et al. (2007) investigated that increasing fine particle concentration aggravated asthma and allergens and these kind of diseases broke out severely in air polluted urban city. $PM_{2.5}$, one of the most adversely influential matters to human, causes cardiac disorder, respiratory diseases which impair pulmonary function and even death (Pope et al., 2015). Not only $PM_{2.5}$ but also PM_{10}, SO_2, NO_2, O_3 and CO are related to hospital admissions (Moolgavkar et al., 1997). In the report conducted in Philadelphia and Pennsylvania in US, 100 $\mu g/m^3$ increase of total suspended particulate raised 10% in mortality of people aged over 65 and 3% in mortality of under 65 (Schwartz et al., 1992). Pope et al. (1991) reported that pulmonary functions of asthmatic patients and fourth, fifth grade students are reduced up to 3%-6% after they were exposed to 150 $\mu g/m^3$ of PM_{10}

Air-side economizer which is operated in commercial, industrial, institutional and large buildings has advantages as a cooling method using outdoor air for reducing HVAC energy consumption. US has reduced HVAC energy consumption installing air-side economizer in large buildings. However, there is an issue to operate air-side economizer because outdoor air quality is not always clean so that Indoor Air Quality (IAQ) could get worse. According to Zhang and Rock (2012) research, 20.7% of China's cities exceed Grade II of National Standard of China and World Health Organization (WHO) report of 2000 showed 80% of the most polluted big cities in the world were located in China. Concentration of $PM_{2.5}$ of these cities was 7 times higher than WHO standard (Chan and Yao, 2008). As research showed before, big cities like Shanghai, Beijing in China and Seoul in South Korea are not free of air pollution. Therefore, this study suggests a method improving IAQ when air-side economizer is operated considering outdoor air quality.

1.1. Research Method

ASHRAE Standard 90.1-2013 defines basic concept of air-side economizer types classified 6 that are fixed dry bulb, differential dry bulb, fixed enthalpy, differential enthalpy, electronic enthalpy, dew-point and dry bulb temperature. These types are selected for use of proper climate zone according to the standard.

This study progressed simulation with differential enthalpy economizer type. To consider IAQ, AQI which is suggested by US Environmental Protection Agency (US EPA) is used as a constraint condition. It is calculated with six pollutants including Ozone, $PM_{2.5}$, PM_{10}, CO, NO_2 and SO_2 that adversely affect human health. AQI of each pollutants follows (1).

$$\mathrm{I_p} = \frac{\mathrm{I_{Hi}} - \mathrm{I_{Lo}}}{\mathrm{BP_{Hi}} - BP_{Lo}} \left(C_p - BP_{Lo}\right) + I_{Lo} \qquad (1)$$

$\mathrm{I_p} =$ $the\ index\ for\ pollutant\ P\ (AQI_P)$

C_p = the rounded concentration of pollutant P
BP_{Hi} = the breaking point that is greater than or equal to C_p
BP_{Lo} = the breaking point that is less than or equal to C_p
I_{Hi} = the AQI value corresponding to BP_{Hi}
I_{Lo} = the AQI value corresponding to BP_{Lo}

In (1), BP_{Hi}, BP_{Lo}, I_{Hi}, I_{Lo} are regulated by Guidelines for the Reporting of Daily Air Quality – the Air Quality Index of US EPA. Calculated AQI presents air quality state by result value. When the value scale is from 0 to 50, air quality state is "Good". Value scale from 51 to 100 indicates air quality state "Moderate", value scale from 101 to 150 indicates "Unhealthy for Sensitive Groups", value scale from 151 to 200 indicates "Unhealthy", value scale from 201 to 300 indicates "Very Unhealthy" and value above 301 indicates "Hazardous".

This study suggests air-side economizer control method that makes air-side economizer operation stopped when AQI level is over 100 (Moderate) even though it can be operated. Fig. 1 shows differential enthalpy economizer considering AQI control algorithm (AQI modified economizer).

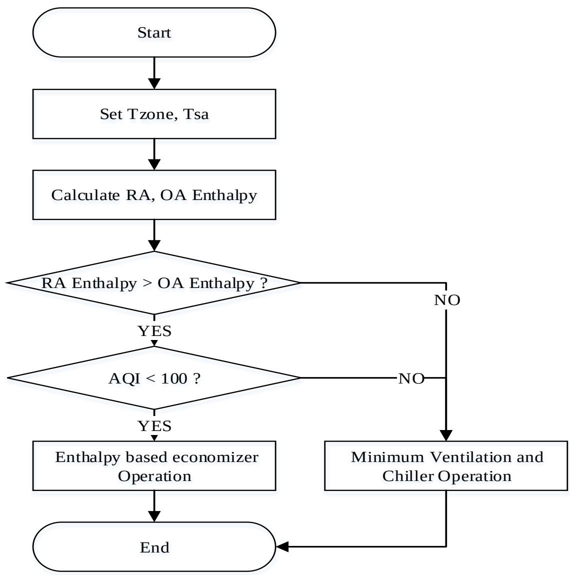


Fig. 1 Flow chart of differential enthalpy economizer considering AQI

2. Simulation

2.1. Simulation Conditions

For conducting simulation study, Energy Plus, Open Studio and Excel programs were used. Table 1 describes a summary for the simulation conditions. In this research, minimum ventilation rate is set in 2.5L/s·person for people and in 0.3L/s·m² for area. Also, occupant density is set in 5 people/100m² which were defined by ASHRAE Standard 62.1-2013 for work space of open office. And this building was assumed that air pollutants were not emitted in office room. Filter also was not installed to analyze between HVAC energy consumption and IAQ clearly, when AQI modified economizer was operated. Simulation was conducted in Seoul, South Korea and in Shanghai, China where AQI is poor and differential enthalpy economizer is able to be operated.

Table 1. Information of building

<table>
<tr><td colspan="3">Building type</td><td>Office building</td></tr>
<tr><td colspan="3">Weather data</td><td>Shanghai/Seoul [IWEC]</td></tr>
<tr><td rowspan="9">Building info</td><td colspan="2">Volume</td><td>10m * 10m * 3m (D * W * H)</td></tr>
<tr><td colspan="2">Area</td><td>100m²</td></tr>
<tr><td colspan="2">Floor</td><td>1</td></tr>
<tr><td colspan="2">Window-Wall ratio</td><td>0.5</td></tr>
<tr><td colspan="2">Temperature setting</td><td>24˚C</td></tr>
<tr><td rowspan="4">U-Value</td><td>External wall</td><td>0.59 W/m²·K</td></tr>
<tr><td>Roof</td><td>0.27 W/m²·K</td></tr>
<tr><td>Floor</td><td>0.50 W/m²·K</td></tr>
<tr><td>Window</td><td>2.27 W/m²·K</td></tr>
<tr><td rowspan="4">HVAC system</td><td colspan="3">VAV system</td></tr>
<tr><td colspan="2">Filter</td><td>Not installed</td></tr>
<tr><td colspan="2">Fan efficiency</td><td>0.5</td></tr>
<tr><td colspan="2">Pump efficiency</td><td>0.6</td></tr>
<tr><td>Office hour</td><td colspan="3">AM 9:00 – PM 6:00</td></tr>
</table>

Climate of Shanghai belongs to temperature humid climate. During January, the coldest month, average minimum temperature is 0.5℃ and average maximum temperature is 7.7℃ that is analogous to the temperature in March of Seoul. During July, the hottest month, average minimum and maximum temperature is 24.8℃ and 31.6℃ respectively. Climate of Seoul also belongs to temperature humid climate. In January, the coldest month, average minimum and maximum temperature is -6.1℃ and 1.6℃ each. In August, the hottest month, average minimum and maximum temperature is 22.1℃ and 29.5℃ respectively

2.2. IAQ and HVAC Energy Analysis

Over all three simulations were conducted. Cases included no economizer, differential enthalpy economizer and AQI modified economizer. Each cases' Indoor concentration of $PM_{2.5}$ was calculated and compared. It is the reason to select $PM_{2.5}$ that it has a considerably effect on AQI and it significantly affects occupant's health especially of respiratory system and cardiopulmonary function (Linares and Diaz, 2010). Another reason to select $PM_{2.5}$ is it impacts on IAQ immediately because it is hard to be captured in filter. Indoor concentration of $PM_{2.5}$ was solved by (2). And also, this study analyzed how much energy consumption increased in HVAC system when comparing to differential enthalpy economizer and AQI modified economizer.

$$\mathrm{V}\frac{\mathrm{dc}}{\mathrm{dt}} = -Q_S(C - C_S) + G \tag{2}$$

V = the Volume of space [m^3]
C = the PM2.5 concentration of indoor air [$\mu\mathrm{g/m}^3$]
$\mathrm{C_s}$ = the PM2.5 cocentration of supply air [$\mu\mathrm{g/m}^3$]
$\mathrm{Q_s}$ = the Volume flow rate of supply air [$\mathrm{m}^3/\mathrm{min}$]
$\frac{\mathrm{dc}}{\mathrm{dt}}$ = the time variant change of PM2.5 concentration [$\mu\mathrm{g}/\ \mathrm{m}^3 \cdot \mathrm{min}$]
G = the amount of PM2.5 emssion rate [$\mu\mathrm{g/min}$]

2.2.1. Shanghai

AQI dataset of Shanghai was provided by Ministry of Environmental Protection of the People's Republic of China.

Differential enthalpy economizer was operated from early February to the end of May and from early October to early December. It is 61,661 minutes (about 1,028 hours) during the course of a year. AQI modified economizer was operated for 52,764 minutes (about 879 hours) of the year. When considering AQI, the result showed that operation was stopped about 8,897 minutes (148 hours) although outdoor air conditions were good for air-side economizer operation.

Fig. 2 presents the amount of time exceeding standard when setting 75 $\mu g/m^3$ as a criterion from the table ($PM_{2.5}$ in average 24 hours of Class II) of Ambient Air Quality Standards, GB 3095-2012 published by Ministry of Environmental Protection of the People's Republic of China.

According to the result, standard overtime of no economizer is 88,878 minutes (about 1,481 hours), differential enthalpy economizer is 90,296 minutes (about 1,505 hours) and AQI modified economizer is 87,740 minutes (about 1462 hours). Operating AQI modified economizer reduced 2,556 more minutes (about 43 hours) of exceeding 75 $\mu g/m^3$ than operating differential enthalpy economizer. It decreased to almost 2.83%. Considering previous studies, it can certainly reduce the risk of diseases: cardiac illnesses, respiratory diseases, allergies etc.

Fig. 3 indicates accumulative amount of indoor $PM_{2.5}$ annually. Grey line represents AQI modified economizer while Orange line represents differential enthalpy economizer and Blue line represents no economizer. The annual accumulative amount difference between differential enthalpy economizer and AQI modified economizer is 151,611.52 μg/m³ (0.58%), which reduced a significant amount.

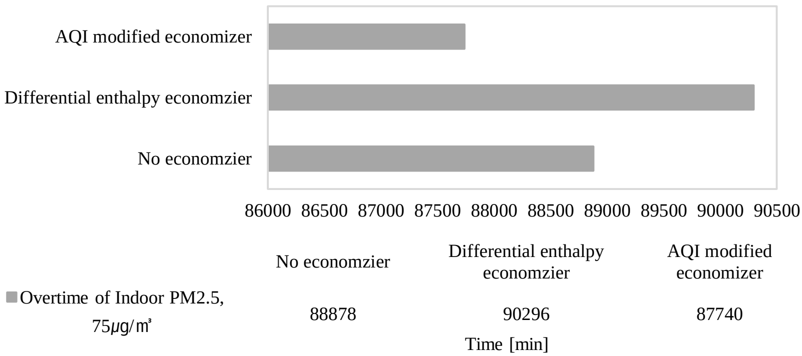


Fig. 2 Overtime of indoor $PM_{2.5}$ concentration, 75 μg/m³

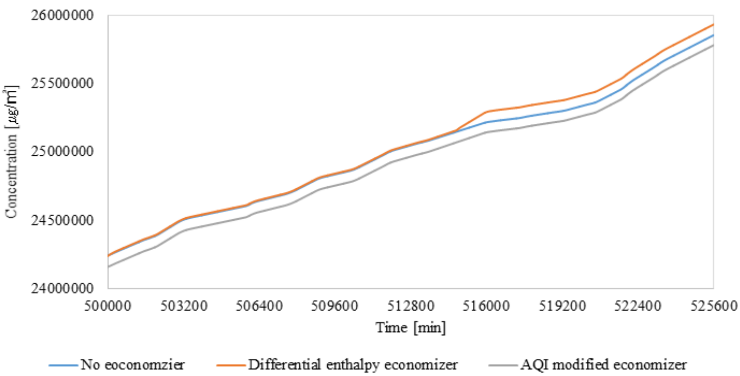
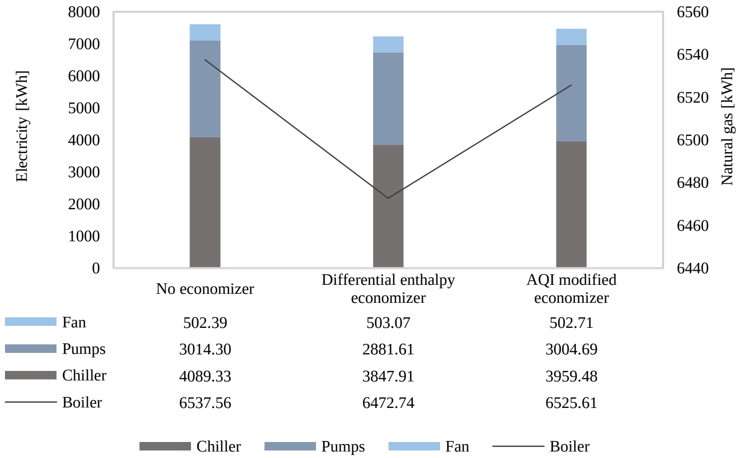


Fig. 3 Duration curve of $PM_{2.5}$, Shanghai

As air-side economizer operation time decreases, however, HVAC energy consumption increases. This energy consumption increase influences the air quality improvement. Indoor air quality affects occupant's health state significantly so that it is more important to improve indoor air quality than to save a little amount of HVAC energy. The following Fig. 4 is a graph shows the annual amount of HVAC energy consumption differences among no economizer, differential enthalpy economizer and AQI modified economizer in Shanghai.

In the case of Shanghai, AQI modified economizer spends 287.15kWh, about 2.10%, more than differential enthalpy economizer's at the same time that it spends 151.08kWh, about 1.07%, less than no economizer. In case of operating AQI modified economizer, it improves air quality derived from 2.83% decreases in 75 μg/m³ overtime of $PM_{2.5}$ while it uses 2.10% amount of HVAC energy more comparing to differential enthalpy economizer's.



	No economizer	Differential enthalpy economizer	AQI modified economizer
Fan	502.39	503.07	502.71
Pumps	3014.30	2881.61	3004.69
Chiller	4089.33	3847.91	3959.48
Boiler	6537.56	6472.74	6525.61

Fig. 4 HVAC energy consumption of each case, Shanghai

2.2.2. Seoul

Seoul's AQI data is based on the date from Airkorea which is public website managed by South Korea Environment Corporation providing real-time air quality.

It was noticed that differential enthalpy economizer operated during March, April, May and October from the simulation. Differential enthalpy economizer was operated for 7,301 minutes (about 122 hours) for a year and AQI modified economizer was operated for 5,588 minutes (about 93 hours) for a year.

There is operating differential enthalpy economizer time gap between in Shanghai and in Seoul because intermediate season in Seoul is short and it is humid during the season. On the contrary, it has not bad weather condition to operate the air-side economizer during the winter in Shanghai so that it is possible to operate the air-side economizer during not only the intermediate season but also the winter.

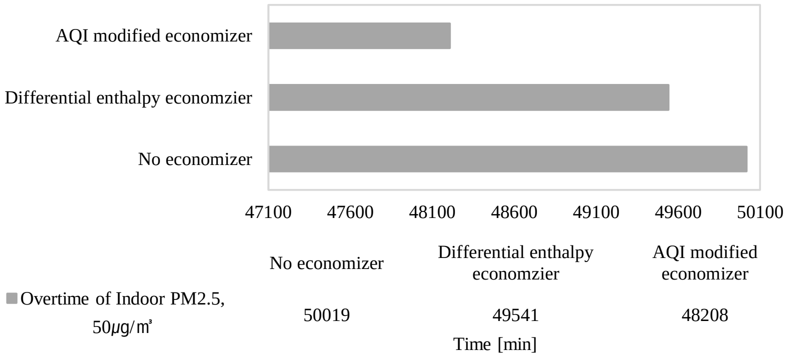


Fig. 5 Overtime of indoor $PM_{2.5}$ concentration, 50 μg/m³

Fig. 5 presents the amount of time exceeding standard when setting 50 μg/m³ as a criterion from enforcement ordinance of framework act on environmental policy ($PM_{2.5}$ in average 24 hours). Considering AQI, it reduced 1,333 more minutes (about 22 hours) of exceeding 50 μg/m³ than operating differential enthalpy economizer. It decreased to almost 2.69%.

Fig. 6 indicates accumulative amount of indoor $PM_{2.5}$ in Seoul annually. When considering AQI, the amount of 48,584.87 μg/m³ (0.34%) decreased comparing to operating differential enthalpy economizer.

When it comes to HVAC energy, Fig. 7, AQI modified economizer consumes 5.86kWh, about 0.03%, more than differential enthalpy economizer's while it spends 17.76kWh, about 0.11%, less than no economizer.

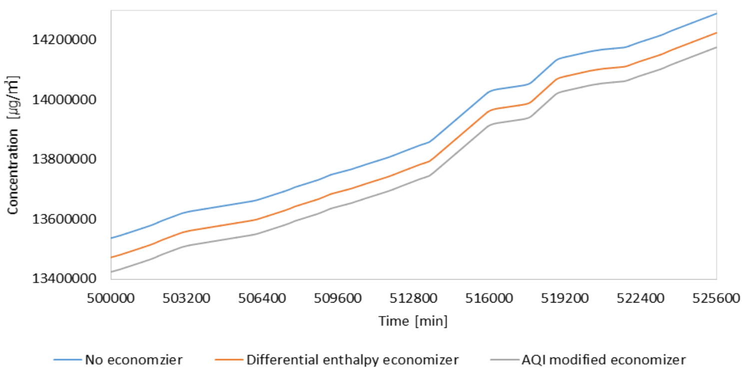
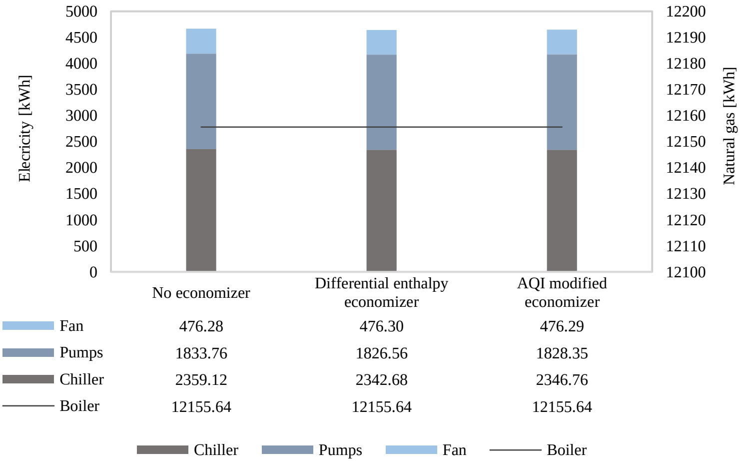


Fig. 6 Duration curve of $PM_{2.5}$, Seoul



	No economizer	Differential enthalpy economizer	AQI modified economizer
Fan	476.28	476.30	476.29
Pumps	1833.76	1826.56	1828.35
Chiller	2359.12	2342.68	2346.76
Boiler	12155.64	12155.64	12155.64

Fig. 7 HVAC energy consumption of each case, Seoul

3. Conclusion

In case of Shanghai, 287.15kWh of HVAC energy is more consumed when operating AQI modified economizer than differential enthalpy economizer. However, it brings out the effect annually to reduce 151,611.52 µg/m³ of accumulative $PM_{2.5}$ and also 42.6 hours of exceeding 75 µg/m³ of China's Standard. As operating AQI modified economizer, in other words, there are 2.10% increase in HVAC energy consumption, 0.58% decrease in accumulative $PM_{2.5}$ and 2.83% decrease in $PM_{2.5}$ 75 µg/m³ overtime annually.

Similarly, in Seoul, 5.86 kWh of HVAC energy is more consumed when AQI modified economizer is operated rather than differential enthalpy economizer. It reduces annually 48,584.87 µg/m³ of accumulative $PM_{2.5}$ and 22 hours of exceeding 50 µg/m³ of South Korea's Standard. That is 0.03% increase in HVAC energy consumption, 0.34% decrease in accumulative $PM_{2.5}$ and 2.69% decrease in of $PM_{2.5}$ 50 µg/m³ overtime annually.

These results show that considering outdoor air quality for air-side economizer brings about significant differences in IAQ. AQI modified economizer improved IAQ in both Shanghai and Seoul.

According to Linares and Diaz (2010), increasing concentration of $PM_{2.5}$ and hospital admissions had linear relation with no threshold. And if the concentration increases from 10 µg/m³ (annual average standard of $PM_{2.5}$ concentration of WHO) to 35 µg/m³, the risk of dying of cardiac and respiratory diseases rises up to 15%. If the concentration of $PM_{2.5}$ decreases from 35 µg/m³ to 25 µg/m³, the mortality drops 6%. Likewise, if the concentration of $PM_{2.5}$ decreases from 25 µg/m³ to 15 µg/m³, the mortality drops 6% as well (WHO, 2005). O'Donnell et al. (2011) also reported that risk of ischemic stroke onset will increase up to 11% to people who had medical history of diabetes, when concentration of $PM_{2.5}$ increased. Referring to post hoc studies, it is shown that if accumulative $PM_{2.5}$ and standard overtime of $PM_{2.5}$ in Shanghai and Seoul decreases, the risk of developing respiratory disease, cardiac disorder and cerebropathia will be reduced.

Acknowledgment

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