IAQ & Energy Impact of Exhaust Air Transfer Ratio

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As requirements for proper ventilation grow more stringent, it is vital to properly consider energy recovery options to meet indoor air quality guidelines and minimize the energy requirements of outdoor air ventilation. To optimize the health benefits of outdoor air ventilation and to offset energy use, many systems use energy recovery devices such as enthalpy wheels or enthalpic plates. These devices transfer heat and moisture between supply and exhaust airstreams to reduce energy loads on the HVAC system.

A perceived risk of energy recovery devices is the potential for the transfer of air and substances from the exhaust airstream to the supply airstream of a ventilation system. This transfer of substances is called exhaust air transfer ratio (EATR)[1] and is depicted in *Figure 1* for the example of an enthalpy wheel. The outdoor air correction factor (OACF) is the ratio of entering outdoor airflow to the gross leaving supply airflow,[1] and is inversely related to EATR. ASHRAE Standard 62.1-2013 states that recirculated Class 2 air shall not exceed 10% of the supply flow, and Class 3 air shall not exceed 5% of the supply flow.[2]

To understand the impact 5% and 10% EATR have on IAQ, the dilution time of a built-up substance in an office and the steady-state concentration of transfer substances in a full classroom are calculated and compared to cases with zero EATR. EATR on an enthalpy wheel can be minimized with the application of a purge sector or with an increase in differential pressures between the supply and exhaust flows, but these methods can increase equipment and operational energy requirements. The effect of EATR specifications less than those defined by ASHRAE on IAQ and the energy requirements resulting from those specifications are examined.

Components of Exhaust Air Transfer Ratio

An enthalpic plate heat exchanger's EATR is due to permeation through the membrane, which depends on the interactions between the substance and the membrane itself.[3] An enthalpic wheel's EATR is due to seal leakage, matrix carryover, and, to a lesser extent, desiccant sorption.[4] Seal leakage is minimized by effective seal design, fan configuration, and by balancing the supply and exhaust flow pressures. Matrix carryover is mitigated by the designed matrix density, wheel depth, and wheel speed. Desiccant sorption of any substance other than water vapor is extremely low and is almost impossible to force,[5] and thus is an insignificant portion of EATR. It is very difficult for a desiccant to adsorb any amount of substances other than water vapor because of

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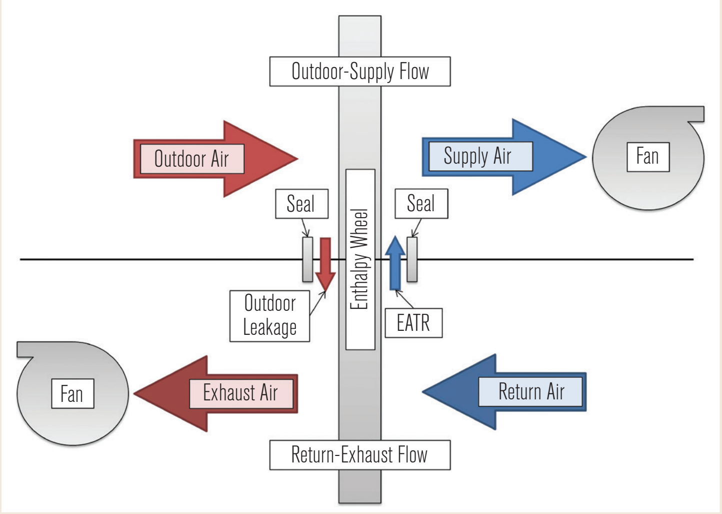
the chemical properties of desiccants. Hayhurst, et al.,[5] examined how much desiccant adsorption of ammonia occurred in hydrated air onto different types of desiccants (specifically molecular sieves Zeolite A and Zeolite 13X). Ammonia was considered the most likely to be adsorbed through the desiccant due to its polarity, small size, and solubility, and yet the desiccant needed 2,620 ppm injected to get 1 ppm to adsorb. To put this in perspective, a human nose can detect ammonia at a mere 5 ppm, and the substance causes unbearable irritation at 140 ppm,[6] further demonstrating the dangerous amount of contaminant required. Hayhurst, et al., concluded that sorption of substances other than water vapor is highly unlikely in any enthalpy wheel application because of the desiccants' selectiveness to water.[5] Because of these factors and design considerations of enthalpy wheels, seal leakage and matrix carryover account for the majority of the total EATR.

FIGURE 1 Enthalpy wheel configuration.



EATR Impact on Indoor Air Quality

To address the most common instances of how EATR impacts indoor air quality, two different types of cases were analyzed. The first case is the substance buildup and dilution time example, and the second case is the steady-state indoor substance concentration example.

Case 1: Calculating Required Time to Dilute a Buildup of Formaldehyde

The first case is fundamentally based on the dilution equation, referenced in the *2015 ASHRAE Handbook—HVAC Applications*.[7]

$$D_t = \frac{V}{r_{vent}} \times \ln\left(\frac{C_{initial}}{C_{final}}\right)$$

V represents the volume of the space, r_{vent} is the fresh airflow ventilation, $C_{initial}$ is the built-up concentration of the substance in the room, and C_{final} is the acceptable substance concentration in the room. D_t is the amount of time required for the room to reach the acceptable concentration.

The fresh airflow ventilation that represents only the fresh incoming air (and no EATR air), r_{vent}, must account for the ventilation air substance concentration, the number of occupants the space is designed for and the EATR expected in the system. This calculates how much of the total supplied airflow is not EATR or ventilation air that contains the prescribed substance.

$$r_{vent} = \left[W_{occupant} - \left(W_{occupant} \times \frac{\%C_{vent}}{100}\right)\right] \times n_{max\ occupants} \times \left(1 - \frac{\%EATR}{100}\right)$$

$W_{occupant}$ is the amount of fresh airflow allotted to each occupant (often referred to as "cfm per person"), $\%C_{vent}$ is the contaminant percentage in the ventilation air, $n_{max\ occupants}$ is how many people the space is designed for, and $\%EATR$ is the percentage of EATR expected in the ventilation system. The occupant term must be at least one; otherwise, the space would be designed without ventilation. If there is any contaminant in the ventilation air or if EATR is greater than zero in the system, then the time to dilution completion will increase.

According to ASHRAE Standard 62.1-2013, an office requires 5 cfm (2.4 L/s) per occupant in addition to 0.06 cfm/ft^2 (0.31 L/s·m^2).[2] From, Kim, et al., the average "private reading room" (akin to a private office) is 205.59 ft^2 (19.1 m^2).[8] Using the ASHRAE Standard 62.1-2013 equation 6.2.2.1,[2] the total amount of ventilation required for this size office with a single occupant is 17.34 cfm (8.18 L/s).

$$V_{required} = \left(1\,\text{occupant} \times 5\,\frac{\text{cfm}}{\text{occupant}}\right) + \left(205.59\,\text{ft}^2 \times 0.06\,\frac{\text{cfm}}{\text{ft}^2}\right) = 17.34\,\text{cfm}$$

With 0% EATR and 0% pollutant in the ventilation air, the fresh air provided equals this requirement.

$$r_{vent} = \left[17.34\text{ cfm} - \left(17.34\text{ cfm} \times \frac{0\%}{100}\right)\right] \times$$

$$1\,\text{occupant} \times \left(1 - \frac{0\%}{100}\right) = 17.34\,\text{cfm}$$

Kim, et al., found the average office studied to have a buildup of formaldehyde of 119 micrograms per cubic meter, or 0.097 ppm.[8] Case 1 uses an acceptable level equal to 0.081 ppm, from WHO/Europe's limits for sensitive people for an exposure of 30 minutes to formaldehyde.[2] The OSHA enforceable limit is 0.75 ppm.[2] Assuming 10 ft (3 m) ceilings in the office, the time to ventilation is calculated.

$$D_t = \frac{2055.9\,\text{ft}^3}{17.34\,\text{cfm}} \times \ln\left(\frac{0.097\,\text{ppm}}{0.081\,\text{ppm}}\right) = 21.37\text{ minutes}$$

At this calculated ventilation rate of 17.34 cfm (8.18 L/s) with no occupants prior to the start of ventilation, the ventilation system would require 21.37 minutes to dilute the formaldehyde from 0.097 ppm to an acceptable level of 0.081 ppm.[2]

This case was recalculated with varying EATRs. Five percent EATR increased the dilution time to 22.5 minutes. The difference was 1.13 minutes. ASHRAE Standard 62.1-2013 states that recirculated Class 2 air shall not exceed 10% of the outdoor air intake flow,[2] so this value was chosen as the maximum allowable EATR in this case. With 10% EATR, the time to dilution increased to 23.75 minutes. The maximum allowable level of EATR (10%) increased the ventilation time required by 2.38 minutes. The results of these calculations are summarized in *Table 1*.

TABLE 1 Summary of dilution time results. Using the inputs as described in Case 1 and within this table, the time to dilution completion may be calculated. As EATR increases, dilution time increases by a minimal amount.

EATR (%)	NON-EATR VENTILATION AIR (cfm)	OFFICE VOLUME (ft^3)	INITIAL SUBSTANCE CONCENTRATION (ppm)	ACCEPTABLE SUBSTANCE CONCENTRATION (ppm)	DILUTION TIME REQUIRED (MINUTES)	ADDITIONAL DILUTION TIME FROM 0 EATR (MINUTES)
0	17.34	2,055.9	0.097	0.081	21.37	–
5	16.47	2,055.9	0.097	0.081	22.5	1.13
10	15.61	2,055.9	0.097	0.081	23.75	2.38

Case 2: Calculating the Steady-State Indoor Carbon Dioxide Concentration

The steady-state indoor concentration equation can be found in Informative Appendix C of ASHRAE Standard 62.1-2013[2] (Equation C-1):

$$r_{vent} = \frac{r_{gen}}{C_{indoors} - C_{vent}}$$

Rearranged, the indoor concentration of a substance can be calculated (note the multiplication of 10^6 is in place for parts per million units):

$$C_{indoors} = \left(\frac{r_{gen}}{r_{vent}} \times 10^6\right) + C_{vent}$$

r_{gen} represents the generation rate of the substance, r_{vent} represents the rate of ventilation, and C_{vent} represents the level of substance in the ventilation air.

The generation rate is calculated as the respiration rate of each occupant multiplied by how many occupants are in the space. Similarly, this can be extrapolated as the emission rate of pollutant *x*, and how many sources of pollutant *x* there are.

$$r_{gen} = \frac{R \times n_{sources}}{0.004047687 \times 60}$$

R is the respiration rate of each occupant, or the emission rate of each pollutant generator, and $n_{sources}$ is the number of occupants, or sources of the pollutant, in the space. The constant in the denominator converts lb/min to L/s.

The ventilation rate calculation, which represents only the fresh incoming air (and no EATR air), must take the level of contaminant in the ventilation air and the EATR of the system into account. This calculation takes the total supplied airflow and calculates how much of that air is not EATR air or ventilation outdoor air containing the prescribed substance. Thus, this equation is almost identical to the fresh airflow ventilation calculation completed for the dilution calculation.

$$r_{vent} = \left[W_{occupant} - \left(W_{occupant} \times \frac{\%C_{vent}}{100}\right)\right] \times$$

$$n_{max\ occupants} \times \left(1 - \frac{\%EATR}{100}\right) \times \frac{1}{2.11888}$$

$W_{occupant}$ is the amount of flow provided for each occupant, $\%C_{vent}$ represents the percent of ventilation air that is made up of the contaminant, $n_{maxoccupants}$ is how many occupants the space is intended for, and is the EATR of the system. The $\frac{1}{2.11888}$ term converts cfm to L/s, and is added here for consistency with the fundamental concentration equation.

TABLE 2 Summary of steady-state concentration results. Using the inputs as described in Case 2 and within this table, the steady-state concentration may be calculated. As EATR increases, the steady-state concentration of CO_2 increases by a minimal amount.

EATR (%)	CO_2 GENERATION RATE (L/s)	NON-EATR VENTILATION AIR (L/s)	CO_2 IN AMBIENT AIR (ppm)	STEADY-STATE CONCENTRATION (ppm)	ADDITIONAL CO_2 CONCENTRATION (ppm)
0	0.0042987514	7.079211659	400	1,007.24	–
5	0.0042987514	6.725251076	400	1,039.20	31.96
10	0.0042987514	6.371290493	400	1,074.71	67.47

For this example, consider a classroom of children. According to Haverinen-Shaughnessy, et al., a child's carbon dioxide respiration rate is 0.001044 lb/min (0.00047 kg/min).[9] ASHRAE Standard 62.1-2013 requires a minimum classroom ventilation rate of 15 cfm (7 L/s) (totaled from 10 cfm/student [4.7 L/s per student] and 0.12 cfm/ft^2 [0.61 L/s·m^2]),[2] and an ambient air carbon dioxide concentration level of 400 ppm was assumed for this calculation. The classroom was assumed to have 100% occupancy. In other words, the classroom has exactly the maximum allowable number of students it was designed for. With these parameters, the indoor carbon dioxide concentration level is calculated to be 607.24 ppm above the ambient level.

$$r_{gen} = \frac{0.001044 \times 1}{0.004047687 \times 60} = 0.0042987514 \text{ L/s}$$

$$r_{vent} = \left[15 - \left(15 \times \frac{0\%}{100\%}\right)\right] \times 1 \times \left(1 - \frac{0\%}{100\%}\right) \times \frac{1}{2.11888} = 7.079211659 \text{ L/s}$$

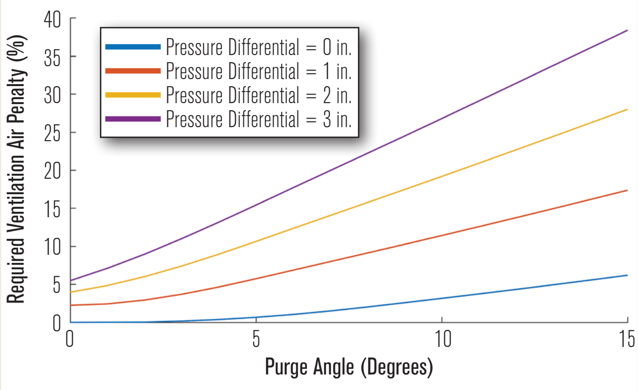
$$C_{indoors} = \left(\frac{0.0042987514}{7.079211659} \times 10^6\right) = 607.24 \text{ ppm} + 400 \text{ ppm} = 1007.24 \text{ ppm}$$

With the ambient carbon dioxide concentration level set to 400 ppm, the absolute calculated indoor carbon dioxide concentration is 1,007.24 ppm. This is well within the "acceptable" air conditions as described by ASHRAE Standard 62.1-2013, which states that 80% of visitors to a new room will find the air acceptable within 700 ppm over the ambient air level.[2]

The same calculation was redone for 5% and 10% EATR. Five percent EATR increased the indoor carbon dioxide level to 639.20 ppm above ambient, which set the absolute indoor level at 1,039.20 ppm. Ten percent EATR increased the indoor carbon dioxide level to 674.71 ppm over ambient, which set the absolute indoor level at 1074.71 ppm. The results of these calculations are summarized in *Table 2*.

In both EATR cases, the indoor air carbon dioxide concentration level is under the 80% majority acceptable limit stated in ASHRAE Standard 62.1-2013 of 1,100 ppm.[2] The increase of carbon dioxide brought on by 10% EATR is not recognizable by occupants, and easily meets the OSHA carbon dioxide limit of 5,000 ppm.[2]

FIGURE 2 Ventilation air requirements as a function of purge and pressure differential.



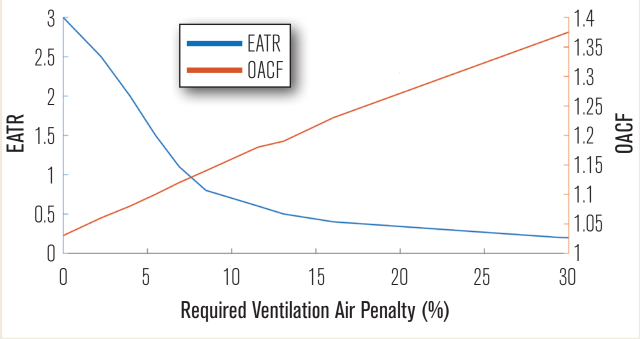
EATR Impact on IAQ Discussion

The two cases examined have found that EATRs within ASHRAE requirements are not a significant concern for dilution time or concentration levels with proper ventilation. With the highest rate of EATR allowed by ASHRAE (10%),[2] the required time to dilute a built-up level of formaldehyde increased by 2.38 minutes. In the steady-state case, a 10% EATR increased the carbon dioxide level indoors by 67.5 ppm to 1,074.71 ppm, and was still well within the 1,100 ppm best practice as prescribed within ASHRAE.[2] Similarly, Huizing, et al., concluded that 15% EATR causes minimal impact on IAQ.[3] Since these studies have shown ASHRAE-accepted EATR levels have minimal effects on IAQ, the cost of designing enthalpy wheels specified with lower than required EATRs must be examined.

The Penalty of Low EATR

Achieving EATRs lower than required by ASHRAE on enthalpy wheels generally requires specifying the wheel with a purge section. Specifying low EATRs generally drives

FIGURE 3 Required ventilation air penalty as a function of pressure differential driven EATR and OACF.



up the amount of air used for purges, which subsequently increases fan energy use. This is especially true in applications with higher air pressure differentials between the return and supply airflows. This relationship is represented in *Figure 2* (Page 16), which shows the estimated ventilation air required for an increase in purge. This estimation is based on 2,800 cfm (1321 L/s) through a wheel using weather data from Louisiana's New Orleans Alvin Callender Field airport.

Alternatively, lower EATRs can be attained by increasing the pressure differential. The outdoor-supply airstream can be specified with a higher pressure such that flow can only transfer into the exhaust. This leads to lowered EATR, but to an increased outdoor air correction factor (OACF).[1]

Figure 3 demonstrates the increase in required ventilation air penalty as EATR is decreased, and how this penalty is due to the increase in OACF because of the difference in pressure across the supply/exhaust interface. This example (2,800 cfm [1321 L/s] through a wheel using weather data from Louisiana's New Orleans Alvin Callender Field airport) shows that a requirement of 0.2% EATR will increase the OACF to about 1.37, which drives the ventilation air penalty up to 30%.

Conclusions

The current work has found that even with the highest EATR allowed by ASHRAE Standard 62.1-2013,[2] the required time to dilute a built-up level of formaldehyde only increases by 2.38 minutes. In the steady-state case, a 10% EATR only increases the carbon dioxide concentration indoors by 67.5 ppm to 1,074.71 ppm, and is still well within the 1,100 ppm best practice.[2] These results are cohesive with the work of Huizing, et al., which concluded that EATR less than 15% causes minimal impact on IAQ.[3]

In addition to the minimal impact to IAQ, the current work has found that as EATR is decreased the OACF is increased drastically, therefore increasing the required ventilation air significantly. For the example used, a requirement of 0.2% EATR increases the OACF to 1.37, thereby driving the ventilation air penalty up to 30% (as seen in *Figure 3*). EATR specifications below the ASHRAE standard have minimal effect on IAQ, and a significant impact on the HVAC system energy requirements.

It is essential to study the effects of EATR in comfort HVAC applications to avoid unnecessarily low EATR designs that drive up equipment and operational requirements. This examination has shown the allowable amount of EATR has a minimal impact on both dilution time required for built-up levels of contaminants and on steady-state indoor concentration levels for the cases examined. With analysis-based understanding of the impact of EATR on IAQ coupled with a full understanding of the energy cost of low EATR designs, enthalpy wheels may be designed and used more efficiently to avoid higher HVAC systems' energy requirements.

References

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