The characterization of aerosol particle contamination as the result of carry-over and cross-over in enthalpy wheels

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Abstract: This paper provides results from a study that characterized the particle distributions found from variable contaminated airstreams in energy recovery ventilators (ERV) during two different test scenarios. The first scenario involved the measurement of the particulate concentrations during an operational situation when the pressure differential forces cross-flow leakage between the exhaust and intake streams. The second scenario involved the characterization of aerosol particulate concentrations from the carry-over contamination when the wheel was not in operation. The findings from the study concluded that if a source of aerosol particulate matter is present in an environment utilizing an ERV system, then cross-over and carry-over contamination will occur proportionally to the amount of aerosol particulate matter released into the system.

1 Introduction

Energy recovery ventilators (ERVs), also known as energy or enthalpy devices, capture the sensible and latent energy that comes from the intake and exhaust streams of a building, and transfer both heat and moisture. Since the adoption of ASHRAE 62 standard, which recommends increased quantities of outdoor air in order to maintain a healthy indoor environment, the need for this technology is greater than ever and, as a result, the interest in total energy recovery is once again on the rise (www.refrige.com, 2009). The purpose of this study was to determine the concentrations of the various size ranges of particulate contamination which may occur due to air leakage. Measured particulates from both cross-flow leakage and carry-over between the two air streams of energy recovery ventilators were included in the data.

The main objectives of the study are as follows:

1. To provide a comparison/contrast between particulate concentrations resulting from either cross-flow leakage or carry-over in an emerging HVAC system design (i.e., energy recovery ventilators).
2. To provide a field example of the typical aerosol size distributions encountered in modern, high efficiency HVAC systems.
3. To elucidate an important aspect involving the increase of outdoor air stipulated by the ASHRAE 62 standard for indoor air quality.

1.1 Energy recovery in building heating, ventilation, and air conditioning (HVAC) design

Available types of ERVs include air-to-air cross-flow heat exchangers, heat pipes, rotary wheels, runaround loops, twin-tower enthalpy recovery loops, and thermosiphons (ASHRAE, 2009). Rotary wheels capture the sensible and latent energy through a revolving enthalpy wheel from the intake and exhaust streams; the size, depth, and speed of the wheel determines the recovery rate. In order to transfer humidity and convective heat, some enthalpy wheels use a desiccant material such as molecular sieve or silica gel (Center Point Energy, 2007).

Performance of the ERVs is typically measured by effectiveness, pressure drop or pumping power of fluids, cross-flow (i.e. the amount of air leakage from one stream to the other), frost control (used to prevent frosting on the heat exchanger), and the overall efficiency (i.e. the ratio of output of a device to its input). The effectiveness of the ERVs refers to the ratio of actual energy or moisture recovered to the maximum possible (ASHRAE Handbook-HVAC Systems and Equipment).

Leakage with rotating wheel systems typically occurs between the intake and exhaust air streams. In most HVAC applications, the mix of ventilation air can range from 5 to 30 percent of the air supplied to the space (Center Point Energy, 2007). Thus, 70 to 95 percent of the air supplied to the space is recycled. In situations where the exhaust air is toxic from an exhaust system and a minimal amount of carry-over is unacceptable, then an ERV is most likely not the correct ventilation system for the facility.

In its sensible energy recovery, an ERV can possibly slightly increase the latent space load due to water vapor transfer. It is therefore important to determine whether the given application calls for a heat recovery ventilator (HRV) or an ERV. ERVs are suitable for applications in schools, offices, residences, and other facility applications that require continuous economical preheating or/and pre-cooling of outdoor-supplied air. The ERV facilitates this transfer across a separating wall made of a material that conducts heat and is permeable to water vapor. Moisture is transferred when there is a difference in vapor pressure between the two airstreams. ERVs are available as desiccant rotary wheels and also as membrane plate exchangers, although other gasses may also pass through the membrane of membrane plate energy exchangers.

In situations where there is an opportunity to transfer heat and mass through the water vapor mechanism (e.g., humid areas, schools, and offices with large occupancies), the ERV technology uses latent and sensible energy to avoid the need for additional heating or cooling. Depending on the orientation of the decreasing vapor stream, the latent energy transfer may be positive or negative. An airstream flowing through an ERV may gain heat energy from the adjoining stream, but will lose the latent energy if it transfers the water vapor to the adjoin stream due to moisture transfer (ASHRAE Handbook-HVAC Systems and Equipment).

Air will move from high pressure to low pressure, and, since there is a low probability that the external and internal air pressures are the same, air leakage is seldom zero. Cross-flow air leakage is usually caused by pressure differentials between airstreams. Carry-over air leakage (specific to wheels) is caused by continuous rotation of trapped exhaust air in cavities in the heat transfer surface, which reverses airflow direction as the wheel rotates and spills this exhaust air into the supply airstream. Air-to-air heat exchangers may experience cross-leakage, cross-contamination, or mixing between supply and exhaust airstreams, which would result in a potentially significant problem if the exhaust gases are toxic or odorous. The rate of cross-leakage varies with heat exchanger type and design, air-stream static pressure differences, and the physical condition of the heat exchanger.

The calculation for carry-over air leakage is expressed by two unitless parameters: the exhaust air transfer ratio (EATR) and outside air correction factor (OACF) (ASHRAE, 2008). Desiccants are applied to an energy recovery wheel serving an exhaust air stream containing contaminants. The desiccant surface is unable to differentiate water vapor from a pollutant, and will transfer some percentage of the pollutant back to the conditioned space (www.refrige.com, 2009). Thus, the need to characterize the extent of this contamination is warranted.

Cross-contamination reduces dilution ventilation effectiveness. When a system employing total energy recovery allows for contaminant carry-over, a significant increase in the amount of conditioned outdoor air is necessary to provide the space with the required indoor air quality. A significant amount of exhaust from toilets or smoking applications is considered unacceptable and therefore cannot be corrected by increasing outdoor air volume (www.refrige.com, 2009).

As there are multiple benefits to operating an energy wheel, it is expected that implementation of these units will continue to increase in the near future. One significant benefit of the energy wheel is its ability to recover latent energy, which occurs in both the heating and cooling seasons. During the cooling season, the outdoor air is pre-cooled before entering the system and significantly reduces the cooling requirements of the air handling unit. When heating is required, this process is reversed and results in the outdoor air being humidified and preheated. This reduction in humidification of ventilation air reduces the heating requirements of the indoor space. Air conditioners use much energy to dehumidify moist air streams; ERVs can reduce the energy load of packaged unitary air conditioners due to their dehumidification enhancement. Utilizing latent recovery potentially doubles the energy savings with the implementation of the sensible-only technology. Ultimately, this will result in a reduction in chiller and boiler capacities.

Incorporating total energy recovery in system design is the cost equivalent to conventional designs when requiring the necessary ventilation requirements and supply air conditions. As a bonus, these systems provide extensive operating cost savings. In addition, these units require little or no maintenance, and tend to be self-cleaning due to the directional air flow reversal of each rotation (ASHRAE, 2008).

1.2 Indoor air quality (IAQ) and human exposure to aerosol particles

With respect to human exposure and indoor air quality issues, the avoidance of such pollutant cross-contamination would provide a significant benefit. Over the last couple of decades, there has been a growing awareness and importance of acceptable indoor air quality (IAQ) in the home and in commercial buildings. Hence, the negative consequences to human health from exposures to respirable particulate in various size ranges have been comprehensively studied and documented by several researchers (Brouwer et al., 2004; Handy et al., 2008; Jamriska et al., 2003; NIOSH, 2005; Sarnat et al., 2003). Depending upon size and morphology, various particles can significantly impact the human health by penetrating deep into the human lungs. Various epidemiological studies conducted have provided evidence for an association between acute particulate matter exposures and increases in mortality and morbidity among people suffering with respiratory and cardiovascular diseases. Other health problems associated with acute exposures to PM included acute asthma exacerbations; bronchitis; acute and chronic respiratory symptoms, such as shortness of breath and painful breathing; increases in the number of hospital admissions for cardiovascular problems, including arrhythmia, myocardial infarction, congestive heart failure, and acute coronary events; and premature deaths (John et al., 2007). Contaminants that present particular problems in the indoor environment include allergens, tobacco smoke, radon, and formaldehyde (ASHRAE, 2009).

The importance of reducing the individual's exposure to airborne particulate matter is emphasized by the U.S. Environmental Protection Agency (USEPA) in its air quality standards. In fact, the USEPA stipulates in the Code of Federal Regulations, Title 40, Part 50 the National Ambient Air Quality Standards (NAAQS) of which particulate matter is considered one of just six criteria pollutants, with maximum limits set at both < 2.5 micron in diameter and < 10 micron in diameter (USEPA, 2010).

The aerosol particulate class covers a vast range of particle sizes, from dust large enough to be visible to the eye down to submicroscopic particles that elude most filters. Particles may be liquid, solid, or have a solid core surrounded by liquid. They are present in the atmosphere at concentrations ranging from one hundred particles per cubic centimeter (in the cleanest of environments) up to millions per cubic centimeter and several hundred micrograms per cubic meter in polluted urban environments. Incomplete combustion of organic substances results in smoke which is small solid and/or liquid particles produced by carbonaceous materials. On average, smoke particles range from 0.1 to 0.3 μm.

Particles are not considered to be smoke or dust unless they are smaller than about 100 μm. 0.1 μm and smaller particles exhibit erratic motion from collisions from air molecules with no measurable settling velocity. This tendency can be characterized similar to gasses and follows Brownian diffusion kinetics, represented by the following relationship:

$$D_p = C_c KT / 3\pi d\mu$$

where D_p is the diffusion coefficient, C_c is the Cunningham slip correction factor, K is the Boltzman constant, T is the absolute temperature, d is the particle diameter, and μ is the gas viscosity (Handy et al., 2007).

Indoor air quality can also be affected by biological hazards. In areas of excessive moisture biological hazards such as mold, mildew, fungi, dust mites, and bacteria may grow in abundance. Mold spores circulate through the air resulting in a range of symptoms and allergic reactions (Klenck, 2000). While there are very few standards or compliance mandates established currently for this type of contamination, the characterization and assessment of bioaerosols in the indoor air environment is a growing area of research which needs to be further addressed.

1.3 Case studies

A study involving the use of an ERV and the consequential improvements in overall IAQ was conducted at the Black Dog Pub in Scarborough, Ontario, Canada (Repace and Johnson, 2006). The ventilation design implemented at this particular pub created a velocity of 30 fpm across ventilation openings; approximately 60 percent of the outside air is sent to the non-smoking area, and 100 percent of the exhaust air is taken from the smoking area. The exhaust air is taken directly back through the rooftop ERV and exhausted outside. With the use of an ERV, non-smoking areas had 80% decrease in reparable particulates, and 50-90% decrease in tobacco specific particulates. In the smoking areas, there was a 70% decrease in reparable particulates, and 40% decrease in tobacco specific particulates (Repace and Johnson, 2006).

Researchers at the University of Minnesota have recently developed an approach involving the testing of resultant cross-contamination of the XeteX AIRotor^{TM} total energy recovery wheel. While the wheel rotation was stopped, there was no detectable cross-contamination; thus, there was no apparent air leakage into the supply. Serious cases predicted an increase of 4% supply air would provide no cross-contamination (Johnson, 1991). The test was conducted using several of the same pollutants employed in the test of a SEMCO^{TM} heat wheel by researchers at Georgia Institute of Technology in 1991. However, three additional pollutants were characterized, including two water soluble compounds which presented a particularly severe carry-over challenge. From this experiment, it was concluded that there was no apparent leakage through the seals of the recovery wheel.

2 Experimental methods

The experimental methodology employed a novel approach for characterizing the aerosol particle distributions measured in the contaminated airstreams in energy recovery ventilators (ERV) during two different test conditions. The first condition involved the measurement of the particulate contamination during an operational event where the pressure differential forces cross-flow leakage between the exhaust and intake streams. The second test condition involved the characterization of aerosol particulate concentrations from the carry-over contamination while the wheel was not in operation. The particulate matter was measured using a HHPC-6 laser particle counter with a resolution of 300 nm and a P-Trak condensation nuclei particle counter (CPC) with a resolution of 20 nm. Since the HHPC-6 measures both quantitatively and qualitatively and the P-Trak only measures quantitatively, the difference between the P-Trak and HHPC-6 (range of 20nm to 300 nm) was taken to determine the concentrations of aerosol particulates present in the various size ranges. Figure 1 shows both the laser particle counter and the CPC being used in tandem during another investigation involving aerosol particulate characterization.

During the sampling event, the inlet temperature was measured to be 36.8°F while the exhaust temperature was recorded as 70.8°F. During the carry-over test, the wheel was operational and three candles were ignited in order to produce a substantial number of particles (e.g., one order of magnitude greater than background) to characterize. On the other hand, for the cross-flow leakage event, the wheel was not operational as the same three candles were lit. The pressure differential set for the carry-over condition was 1:1 while it was set for the cross-flow leakage condition at 0.137. Initially, a baseline test was run with no candles burning in the chamber. The test conditions for this baseline test were 49.4°F (inlet), 69.8°F (exhaust), and a 0.5 – 0.6 pressure differential. Figure 2 provides a photograph of the maintenance panel area on the supply air duct used for the study.

Once the experimental conditions were reached, readings were taken at the maintenance panel on the supply air duct using both the P-Trak Particle Counter and the ARTI HHPC-6 Laser Particle

Counter. This procedure was repeated 5 times in increments of 20 minutes each, respectively. Particulate counts were also taken of the outside air using both the P-Trak CPC and the HHPC-6 laser particle counter immediately after a reading from the supply duct. The outdoor air samples were taken in order to approximate the outdoor air particulate concentrations contributing to the overall count and the respective size ranges. This procedure was also repeated 5 times and in increments of 20 minutes in length.

The measurements were recorded for seven distinct ranges. These ranges were as follows: 20 nanometers to 0.3 micron, 0.3 – 0.5 micron, 0.5 – 0.7 micron, 0.7 – 1.0 micron, 1.0 – 2.0 micron, 2.0 – 5.0 micron, and greater than 5 micron.

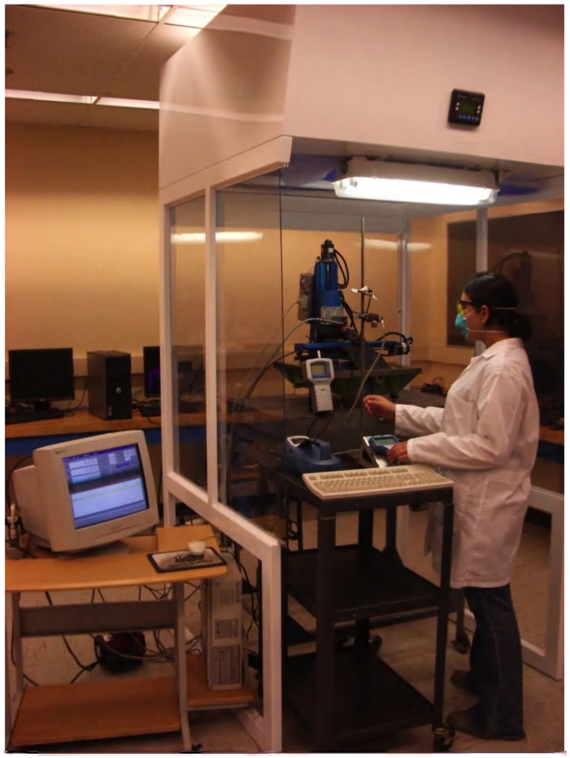

Figure 1 – Use of CPC and laser particle counter in lab research

Figure 2 – Supply air duct maintenance panel

3 Data and results

The data and results from the study are given in Tables 1 through 3 below. Table 1 provides the baseline concentrations of particles for both the carry-over and cross-over tests. Table 2 gives the particle concentration values found for the three test runs involving cross-over conditions while Table 3 does the same for the runs involving carry-over conditions. The "Exhaust" column = exhaust duct from chamber; the "Supply" column = supply to chamber; the "Intake" column = intake into ERV; the "Room" column = environmental chamber; the "Percent Difference" column = (Supply-Intake)/Intake; and the "Particle Sizes < 0.3 micron" row = P-Trak (pt/L) – (∑particle sizes 0.3 pm to >5 pm).

Table 1 – Baseline Particle Concentrations

	Baseline Test (Cross-Over)					Baseline Test (Carry-Over)				
Particle Sizes (pt/l)	*Exhaust*	*Supply*	*Intake*	*Room*	*Difference*	*Exhaust*	*Supply*	*Intake*	*Room*	*Difference*
0.3 - 0.5 micron	10177	15762	19627	11195	-20%	12751	18370	20168	9359	-9%
0.5 - 0.7 micron	1480	2400	2970	1568	-19%	1924	2811	3123	1401	-10%
0.7 - 1.0 micron	300	563	747	323	-25%	415	675	794	302	-15%
1.0 - 2.0 micron	176	391	547	189	-29%	273	473	583	189	-19%
2.0 - 5.0 micron	53	129	211	78	-39%	70	170	221	60	-23%
> 5.0 micron	2	6	30	6	-80%	5	8	22	10	-64%
P-Trak (average) (pt/cm^3)	611	1130	2100	533	-	753	1510	2530	603	-
P-Trak (average) (pt/l)	611000	1130000	2100000	533000	-46%	753000	1510000	2530000	603000	-40%
Particle Sizes < 0.3 micron	598812	1110749	2075868	519641	-46%	737562	1487493	2505089	591679	-41%

Table 2 – Cross-Over Particle Concentrations

	Test #1 (Cross-Over)				
Particle Sizes (pt/l)	*Exhaust*	*Supply*	*Intake*	*Room*	*Difference*
0.3 - 0.5 micron	124341	13049	125642	113499	-90%
0.5 - 0.7 micron	5990	1325	17607	7311	-92%
0.7 - 1.0 micron	491	506	208	655	143%
1.0 - 2.0 micron	201	86	854	257	-90%
2.0 - 5.0 micron	30	1	268	49	-100%
> 5.0 micron	0	1	13	3	-92%
P-Trak (average) (pt/cm^3)	170000	44500	14500	77000	-
P-Trak (average) (pt/l)	170000000	44500000	14500000	77000000	207%
Particle Sizes <0.3 micron	169868947	44485032	14355408	76878226	210%

	Test #2 (Cross-Over)				
Particle Sizes (pt/l)	*Exhaust*	*Supply*	*Intake*	*Room*	*Difference*
0.3 - 0.5 micron	129273	121716	128474	151059	-5%
0.5 - 0.7 micron	7815	13665	17740	9227	-23%
0.7 - 1.0 micron	694	1446	1960	868	-26%
1.0 - 2.0 micron	279	518	722	344	-28%
2.0 - 5.0 micron	34	75	165	64	-55%
> 5.0 micron	0	1	3	19	-67%
P-Trak (average) (pt/cm^3)	140000	33500	6350	60000	-
P-Trak (average) (pt/l)	140000000	33500000	6350000	60000000	428%
Particle Sizes <0.3 micron	139861905	33362579	6200936	59838419	438%

	Test #3 (Cross-Over)				
Particle Sizes (pt/l)	*Exhaust*	*Supply*	*Intake*	*Room*	*Difference*
0.3 - 0.5 micron	178750	125707	130932	178354	-4%
0.5 - 0.7 micron	8639	16061	18223	8285	-12%
0.7 - 1.0 micron	773	1740	2264	713	-23%
1.0 - 2.0 micron	291	788	1264	278	-38%
2.0 - 5.0 micron	48	280	930	83	-70%
> 5.0 micron	1	11	69	29	-84%
P-Trak (average) (pt/cm^3)	96000	34500	7850	55000	-
P-Trak (average) (pt/l)	96000000	34500000	7850000	55000000	339%
Particle Sizes <0.3 micron	95811498	34355413	7696318	54812258	346%

Table 3 – Carry-Over Particle Concentrations

	Test #1 (Carry-Over)				
Particle Sizes (pt/l)	*Exhaust*	*Supply*	*Intake*	*Room*	*Difference*
0.3 - 0.5 micron	73298	109168	125718	67366	-13%
0.5 - 0.7 micron	6055	12356	16201	5609	-24%
0.7 - 1.0 micron	596	1283	1854	555	-31%
1.0 - 2.0 micron	253	522	968	240	-46%
2.0 - 5.0 micron	42	84	805	89	-90%
> 5.0 micron	4	0	119	41	-100%
P-Trak (average) (pt/cm^3)	19000	6050	5050	12500	-
P-Trak (average) (pt/l)	19000000	6050000	5050000	12500000	20%
Particle Sizes < 0.3 micron	18919752	5926587	4904335	12426100	21%
	Test #2 (Carry-Over)				
Particle Sizes (pt/l)	*Exhaust*	*Supply*	*Intake*	*Room*	*Difference*
0.3 - 0.5 micron	69513	108393	124207	65473	-13%
0.5 - 0.7 micron	5843	12966	58893	5761	-78%
0.7 - 1.0 micron	587	1404	1756	606	-20%
1.0 - 2.0 micron	248	557	683	238	-18%
2.0 - 5.0 micron	42	81	124	54	-35%
> 5.0 micron	3	0	7	22	-100%
P-Trak (average) (pt/cm^3)	16000	6150	5000	6300	-
P-Trak (average) (pt/l)	16000000	6150000	5000000	6300000	23%
Particle Sizes < 0.3 micron	15923764	6026599	4814330	6227846	25%
	Test #3 (Carry-Over)				
Particle Sizes (pt/l)	*Exhaust*	*Supply*	*Intake*	*Room*	*Difference*
0.3 - 0.5 micron	79548	106435	128872	65067	-17%
0.5 - 0.7 micron	5953	12461	17498	5962	-29%
0.7 - 1.0 micron	577	1342	1962	599	-32%
1.0 - 2.0 micron	231	552	791	244	-30%
2.0 - 5.0 micron	42	71	149	48	-52%
> 5.0 micron	1	0	8	10	-100%
P-Trak (average) (pt/cm^3)	10150	4650	5450	7600	-
P-Trak (average) (pt/l)	10150000	4650000	5450000	7600000	-15%
Particle Sizes < 0.3 micron	10063648	4529139	5300720	7528070	-15%

4 Discussion of results

The baseline test showed an overall lower particulate measurement from the environmental chamber due to normal operating parameters. In all of the micro particle cases, there was a negative percent difference, which demonstrates that the filter reduces the particulates entering the ERV before entering the supply duct. Due to the air quality of the baseline test, there was not a considerable quantity of particles to cause significant impact on contamination. These trends are similar for both cross-over and carry-over.

The carry-over tests showed a slight percent increase in aerosol particles between the intake into the ERV and the supply duct into the environmental chamber. The probable cause of the increase in particle counts is the carry-over contamination due to the addition of the candles from the exhaust stream of the environmental chamber. A number of factors effect indoor particle levels. Influential factors include the number of people and their activities, building materials and construction, and the HVAC system conditions. The HVAC conditions are affected by outside conditions, ventilation rate, and air-conditioning and filtration system. Furthermore, the particles ranging in size from 0.3 μm to >5 μm showed a decrease in the supply duct compared to the intake most likely due to the filtration and lack of contaminant carry-over. Test 3 showed a negative relationship, contrary to test 1 and 2, which may be attributed to measurement error.

The cross-over tests showed a significant percent increase in aerosol particle counts between the intake into the ERV and the supply duct into the environmental chamber. The probable cause of the increase in particle counts is the carry-over contamination due to the addition of the candles from the exhaust stream of the environmental chamber and the pressure differential between the supply and exhaust streams through the ERV. Like the carry-over tests, the particles ranging in size from 0.3 μm to 5 μm showed a decrease in the supply duct compared to the intake most likely due to the filtration and lack of contaminant cross-over. However, the 0.7 μm measurement in test 1 showed an increase in particles, which is most likely due to a measurement error.

The potential measurement errors for this study include measurement sequencing, instrument resolution/range constraints, and operator error. The impact of these errors could be minimized in future comparable studies by using computer control for sequencing, more sophisticated particle counters to enhance resolution/accuracy, and/or identifying outliers in the data and re-sampling.

4 Conclusion

The findings conclude that if a source of aerosol particulate matter is present in an environment utilizing an ERV system, then cross-over and carry-over contamination will occur proportionally to the amount of aerosol particulate matter released into the system. By positioning the blowers to encourage leakage of outside air to the exhaust airstream, cross-contamination can be reduced. Installation of a purge section onto a heat exchanger should also reduce contamination resulting from carry-over.

Future efforts will involve the measurement and segregation of the ultrafine particle sizes into additional distinctive size ranges. In addition, microscopy will be used to look at the morphology of the ultrafine particles, with the intent of identifying trends in particle distributions in this type of energy efficient HVAC systems as well as the characterization of aerosol kinetics throughout the units.

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