

Conservation of Mass: An Old Principle That Needs More Usage in Hot & Humid Climates

B. K. Browning, PE
Vice President

Gwendolyn McKinney
President

KWR Engineering Services, LLC
Austin, Texas

ABSTRACT

Conservation of mass is such a basic principal that most designers no longer consider it for most design calculations. Design phase commissioning checks on several recent projects indicate designers should include conservation of mass calculations in the design. Recent retro-commissioning project indicate the concept should be considered by building owners and operators as well.

INTRODUCTION

Conservation of mass is a fundamental principal of engineering. While conservation of mass is not sufficiently accurate for some applications (e.g. nuclear), the principal is completely applicable to HVAC applications. As with all fundamental principals it can be applied to various size areas of interest for entire buildings to individual rooms. Unfortunately, commissioning findings on many projects indicate that designers and building operators are trying to violate conservation of mass without recognizing it. The results can cause trouble and major building damage in hot and humid climates.

Discussed here are the application of conservation of mass of water into a space (building or room) and conservation of mass of air into a space. Simplified estimate calculations for each are discussed.

Conservation of Mass

The basic conservation of mass equation is shown in Equation 1.

$$m_{in} - m_{out} = m_{stored} \quad (\text{Eq. 1})$$

$$\frac{dm_{in}}{dt} - \frac{dm_{out}}{dt} = \frac{dm_{stored}}{dt} \quad (\text{Eq. 2})$$

In words, the sum of the masses in minus the sum of the masses out is equal to the mass stored in the space of interest (control volume). The conservation of mass equations can also be stated on a rate basis as shown in Equation 2. Equation 2 stated in words, says the sum of rate of mass flows in minus the sum

of the rate of mass flows out equals the rate of mass stored in the control volume.

The principal of conservation of mass and the equations can be found in entry level chemistry, physics, thermodynamics and other books. Conservation of mass has exceptions, but should be completely applicable to HVAC and building applications.

Conservation of Mass of Water

The first application of conservation of mass should be to water into and out of a building. For most buildings, it is preferred that water not be stored in the building. Straube¹, Lstiburek², and many ASTM authors have published extensively water damage occurs when the moisture stored exceeds the moisture storage capacity of the material. Lstiburek points out that the transition of building materials from masonry, to wood, to gypsum products on metal framing reduced the moisture store capacity significantly with each step. So most buildings can store moisture for some short time period, but when averaged over some 'reasonable' time period should not be greater than zero. (What a 'reasonable' time period is dependent on the building, occupants, sensitivity of materials in the building, etc. and is left to the designer. Harriman³ shows data that indicates the reasonable time period is less than an hour for buildings containing papers / books.) The conservation of mass of water for a building can be reduced to say the water leaving the building should be equal to or greater than the water entering the building.

Estimating the mass of water entering a space can be non-trivial. Fortunately, for most spaces a first approximation can be made by considering the water introduced by ventilation air, people, and infiltration. Harriman shows representative moisture loads for several different occupancies. For a retail space, Harriman⁴ indicates 90% of the moisture load is in the ventilation, people and infiltration. Three items should be noted about this estimate. First, these are the 'known' and expected moisture loads. Unexpected loads or 'unknown loads' will probably

increase the estimate if included. Second, infiltration moisture loads are under the control of the design and construction teams and are generally assumed to be insignificant. Testing, however, shows infiltration to be a very significant moisture load and Persily⁵, Cunningham⁶ and the ASHRAE Fundamentals Handbook warns the user of this. Third, the areas usually considered to be significant moisture loads (doors, windows, water permeance through envelope, wet surfaces, domestic loads, etc.) add up to less than ten percent of the typical moisture load.

The mass of water out of a space can also be estimated to a first approximation. Typically, the HVAC system is the primary means to remove moisture from a space.

Air conditioning systems remove moisture from the air as a byproduct of cooling the air. The air conditioning system moisture removal is typically the most significant amount of moisture leaving the space. Manufacturer’s performance literature lists the latent cooling capacity (energy removed by the moisture removal) for a system at specific conditions. The moisture removal indicated however, is for steady state conditions. In other words, the air conditioning system never started, stopped, or changed the operating temperature / humidity of the conditioned space. Those are not real-world operating conditions for most air conditioning systems.

In 2002, Browning⁷ published a simplified method to estimate the moisture removal capacity of a direct expansion (DX) system operating at part load conditions. The method was based on a 1998 paper by Henderson⁸ and matched test data for many residential and light commercial DX systems. The simplified method is summarized in Figure 1 and the paragraphs below.

Figure 1 shows the latent capacity degradation model originally by Henderson in a more usable form for conservation of water mass calculations. The sensible heat ratio (SHR) and the fraction of the steady state latent heat ratio (%LHRss) are shown as a function of compressor run time fraction.

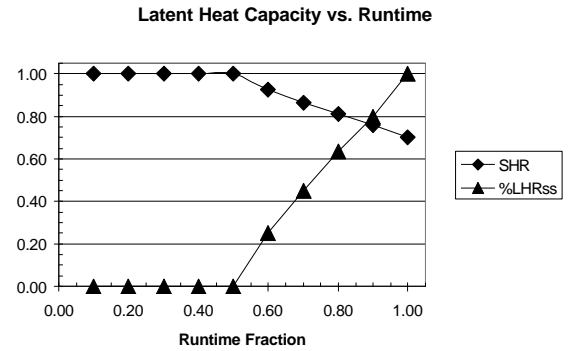


Figure 1 - Sensible Heat Ratio and Fraction of Steady State Latent Heat Ratio versus Runtime Fraction

A very important observation on Figure 1 is that moisture removal capacity (or latent capacity) is virtually zero unless the unit runs more than half the time.

To a first approximation, the latent degradation model shown in Figure 1 is close to linear between zero LHR at 50% runtime fraction and the equipment steady state LHR at 100% runtime fraction. The simple linear approximation is conservative (more latent heat removed than approximated) and is very simple to estimate using the relation in Equation 3.

If runtime fraction is = 50% - %LHRss = 0

If runtime fraction is > 50% - %LHRss = 2x-1

$q_l = \text{Rated Latent Capacity} * \%LHR_{ss}$

mass of water removed per hour = q_l / h_{fg}

Where:

$x = \frac{\text{equipment sensible capacity at condition}}{\text{space sensible load at condition}}$

$q_l = \text{latent capacity at actual condition}$

Rated Latent Capacity = Manufacturer’s published latent capacity at actual condition

$h_{fg} = \text{heat of vaporization, typ. } 1076 \text{ BTU/lb}$

(Eq. 3)

Using Equation 3 it is possible to estimate the moisture removed by a DX air conditioner at part load conditions during design.

The mass of water into or out of a space from each infiltration or ventilation flow can be estimated using Equation 4. Note – as will be discussed under conservation of air mass, all flows into the space will exhaust somewhere and all exhaust will be replaced by a flow from somewhere.)

$q_l = 4840 Q (W_{in} - W_{out})$

mass of water removed per hour = q_l / h_{fg}

Where:

Q = flow rate of air in/out of space, cfm
 W_{in} = humidity ratio of air entering,
 lb(water) / lb(dry air)
 W_{out} = humidity ratio of air leaving,
 lb(water) / lb(dry air),
 typ. 0.009 for 74 F/50% RH
 h_{fg} = heat of vaporization, typ. 1076 BTU/lb

(Eq. 4)

Note that in Equation 4 the only variables that change significantly are the air flow rate and the humidity ratio of the air into the space. The humidity ratio of the air leaving the space is typically at the space conditions. For example, if the space is intended to be maintained at 74°F and 50% relative humidity, all air leaving the space will have a humidity ratio very near 0.0091 pounds of water per pound of dry air. However, any infiltration or unconditioned ventilation air will have a humidity ratio of 0.018 pounds of water per pound of dry air at 80°F and 80% relative humidity (typical summer morning conditions).

Ventilation with outdoor air is effective at removing moisture from a space in dry climates or dry conditions (e.g. heating season). However, in humid climates the outdoor air humidity ratio is above the desired space air humidity ratio for virtually all of the cooling season. Therefore, any attempt to ventilate with outdoor air to remove moisture from a space will actually increase the moisture in the space. The same is true of exhausting air from a space to remove moisture. Exhausting air from a space can only approach the moisture content of the air that replaces the air exhausted. In humid climates if the replacement air is from the outside it will most likely be wetter than the desired space humidity.

Using the estimates discussed above, a conservation of water mass can be calculated. In the experience of the author these estimates typically show the desired condition of no water storage at the ASHRAE cooling design point on most designs. However, if the same conservation of water mass is calculated at the ASHRAE dehumidification condition, light commercial designs frequently show undesirable water storage in the space. If the storage of water in the space occurs for short periods of time separated by longer periods of water removal, this may not cause problems. In reality though, many designs are checked and found to be storing water most of the cooling season.

The conservation of water mass can be used on an entire building. However, it is better used on a room – by – room basis. Rooms with high ventilation loads typically have moisture problems while rooms with low ventilation loads may not. Conservation of water

mass can also be used to determine when ventilation air preconditioning is required. It can also show when staging multiple air conditioning systems may solve a moisture control problem.

One problem with conservation of water mass is that only known water flows are included and only the most significant of those (ref the 90% moisture flows mentioned above – if a moisture flow is not considered then it is ‘assumed to be zero’). The reader is invited to include any and all flows that the reader feels are important. It is common to find designs introduce more water into the space at the 90% estimate discussed here. As such, there is no capacity for the remaining 10 %, the unknowns, or those times when the ASHRAE design point is exceeded.

Conservation of Mass of Air

Conservation of mass of air works the same as for water. However, most buildings have even less storage capacity for air than for water. Building materials do not absorb air and are not tight enough to change the internal pressure significantly. A pound of air into the space will very quickly translate to a pound of air out of the space. To a first approximation, this can be extended to a cubic foot of air into the space will quickly translate to a cubic foot of air out of the space. Density differences during the cooling season will only induce about a 10% error by using air volume instead of air mass. The approximation does get somewhat worse (more than 10% error) for high pressure, very hot, very cool, or very wet air. The reader should evaluate the accuracy needed for a project and adjust their calculations appropriately.

A typical duct system design does not schedule flow rates for return grills. If the building is one large open area, that should not cause problems. However, if there are several return grills on a return duct, each return flow should be scheduled for the supply air to the space minus the ventilation fraction for the supply. Unscheduled return air flows are likely to cause the return grill closest to the air handler to have too high a flow and depressurize that space. The principal of conservation of mass of air into each space should be applied and checked.

Infiltration can be reduced by maintaining the building under a positive pressure with respect to the outside. Most designers use the ‘rule of thumb’ that to assure a building is under “positive pressure”, there should be slightly higher total ventilation flow than exhaust flow from the building. This is a valid concept. However, hidden in that ‘rule of thumb’ are major assumptions that can be major problems.

One of those assumptions is that all spaces inside the building are much better connected (less flow resistance) to each other than they are to the outside. The literature shows many cases where this assumption does not hold true. In this author's investigations, interior partitions are frequently sealed tightly to the roof deck with fire stopping while the building envelope is left unsealed (e.g. coping overlaps parapet wall for water protection but no attempt is made to air seal the joint). The result is internal building spaces are well air sealed from each other but not from the outside.

Another assumption is that building air barrier is relatively 'tight' (restricts air flow into or out of a building). Cummings⁵ reports that the average of the 70 small commercial buildings tested had an air change per hour rating at 50 Pascal (ACH50, 50 Pascal is 0.2 inches water column) of 20. That means that the volume of air in the building was exchanged with the outside 20 times per hour with a pressure difference equivalent to a 25 mile per hour wind.

The assumption of a 'tight' air barrier is rarely achieved without extraordinary effort. In the author's testing, it is rare to find small commercial buildings that have a positive pressure of at least 1 Pa. Since a Pascal is such a small unit of pressure (1/250 inches of water column), if one Pascal is not found then the building is at best unpressurized. A more frequent finding is any pressurization intended in the design has been overcome by other phenomenon (e.g. stack effect) and the building is negatively pressurized. Harriman⁹ suggests the HVAC designer estimate air leakage between 0.10 cfm per square foot of envelope (envelope area, not floor area) for a tight building and 0.60 cfm per square foot of envelope for a rather loose building. It should be noted that non-traditional construction techniques and workmanship are required for a tight building. The estimated air exchange needs to be included in the HVAC sensible and latent load calculations.

The principle of conservation of air mass is extremely important for restaurants. Typically, kitchens are designed with the required and/or desired exhaust fans & hoods. Makeup air is supplied for about 80% of the exhaust flow.

Pressurization Calculation				Exhaust			
Supply							
Mark	Continuous CFM	Intermittent CFM		Mark	Continuous CFM	Intermittent CFM	
RTU-1		50		EF-1		450	
RTU-2		800		EF-2		150	
RTU-3		500		EF-1K		1100	
RTU-4		300		EF-2K		1100	
RTU-5		200		EF-3K		1100	
RTU-6		50		EF-4K		1100	
MAU-5K	500			EF-5K	833		
MAU-6K	1485			EF-6K	2475		
MAU-7K	2173			EF-7K	3621		
MAU-8K	1660			EF-8K	2767		
	<u>5818</u>	<u>1900</u>			<u>9696</u>	<u>5000</u>	
Highest Building Pressurization Flow							
P hi	5818	+	1900	-	9696		
	-1978 (should always be greater than zero)						
Lowest Building Pressurization Flow							
P low	5818	-	9696	-	5000		
	-8878 (should always be greater than zero)						
(Does NOT include +/- 10% tolerance on balancing)							

Figure 2 – Example conservation of air mass estimate from conservation of air volume. Minimum and maximum pressurization can be estimated from continuous and intermittent flows as shown.

Conservation of mass shows that the remaining 20% of the exhaust flow PLUS the air needed for building pressurization must be supplied from other sources. Those other sources are typically the ventilation air for the dining room or other parts of the building. Testing of restaurants both large and small shows that most are significantly depressurized. Some of the restaurants were depressurized enough to back draft exhaust flows. A check of the conservation of air mass would indicate the source and magnitude of depressurization.

Figure 2 is an example of a conservation of air mass calculation for a small restaurant. The volume flow rates are used instead of mass flow rates for simplicity. The air supply flows are totaled for continuously operating fans and for intermittently operating fans. The same is done for the exhaust flows. Then the net flows for maximum building pressurization and for minimum pressurization are calculated. The building should operate between those points at all times. As indicated in the example, this restaurant was found to be significantly depressurized under all condition. This building is located in a humid location and should be expected to have a large flow of wet outside air through the building at all times.

Comments from both designers and in operating personnel indicate a better understanding of conservation of air mass is needed. Both designers and operations staff have indicated their belief that energy is saved by turning off ventilation or makeup air fans. To a first approximation, conservation of air mass indicates that if one cfm of air is exhausted, one cfm of air was supplied to replace it. If the makeup and exhaust air were properly balanced with both operating, then turning off the ventilation or makeup air fan does not reduce the exhaust air or the outside air introduced into the building. Since the building cannot 'store' air to continually exhaust, the air exhausted will be replaced by air from outside. The real difference is when the exhausted air is replaced through ventilation or makeup fans, it enters through a known path where it can be filtered and conditioned. When those fans are turned off, the replacement air is drawn through many unknown leakage paths through the building envelope. Those leakage paths can be widely distributed so there is little chance of filtering or conditioning. The leakage paths are frequently undesirable paths like loading docks, garbage chutes, plumbing chases, etc.

If there is a positive aspect to turning off the makeup air it is that the replacement air is frequently distributed across other portions of the building where other systems may handle the cooling load. In other words, the cooling and dehumidification load may be moved from the zone with the exhaust flow to

other zones where other air conditioning systems MAY be better able to handle the load.

Combination of Conservation of Mass of Air and Water

Conservation of air mass estimates into a space can indicate when infiltration flows will be 'high'. Infiltration of humid outdoor air introduces water mass in the space in hot & humid climates. A conservation of water mass calculation should include the water introduced by infiltration. Unfortunately, infiltration rates are highly dependent on parameters that are not determined during design (e.g. workmanship). The result is designers must use an assumed infiltration rate to complete the design. Unfortunately, a common design stage commissioning finding is zero infiltration was assumed (because it was ignored) in a space that is depressurized because the principal of conservation of air mass was not utilized. Either conservation of mass estimate can be an indication of trouble. Combined, they are a major indication of trouble.

In the case shown in Figure 2, the mass of water introduced by the 1978 cfm outside air (assumed to be at 74°F dew point) and the exhausted air (assumed to be at 55°F dew point) is roughly ½ pound of water per minute. This water has to be removed by the mechanical equipment continuously. At the 8878 cfm air flow imbalance, the air conditioners must remove roughly 2.5 pounds of water every minute just to offset the known air flow imbalance. Assuming a sensible heat ratio of 0.7, it would require between 4 tons (for 1978 cfm imbalance) and 19 tons (for 8878 cfm imbalance) running continuously just to remove the water introduced by the air flow imbalance. It is doubtful a designer would intentionally design a mechanical system with this large an imbalance.

Note that this paper discussed 'first estimates' or approximations instead of very accurate calculations. These estimates are short cuts to quickly indicate a potential problem. More accurate calculations can be done if warranted. However, if the estimates indicate a problem (depressurized space or water stored in the space), it is a significant concern and should be addressed. The converse is not true. If the conservation of mass calculation does not indicate problems, it is not a guarantee that problems will not occur.

CONCLUSIONS

Conservation of mass is a fundamental principal of engineering. The principal is completely applicable to HVAC applications. Approximations can be made with reasonable accuracy as discussed in this paper. The approximations will quickly highlight a significant problem, but cannot verify all problems will be avoided. However, if the approximation indicates problems a more detailed calculation and review should be performed. A conservation of water mass estimate in a space should be conducted in hot & humid climates. If the estimate indicates water is stored in the space under high sensible load conditions, major problems should be expected. Most HVAC space designs indicate water is not stored in the space under high sensible load conditions. However, many of the same designs indicate water will be stored in the space at the ASHRAE dehumidification design point. Most modern buildings are not capable of storing water in the space without damage. Also, these estimates are based on 'known' moisture loads. It is desirable to have some additional capacity to handle unknown or unexpected moisture loads.

Conservation of air mass estimates are also useful methods for identifying potential problems. Few, if any buildings will 'store' significant mass or volume of air. Therefore, conservation of air mass indicates that the mass of air into and out of a space remain approximately equal. This relation can be used to identify pressure imbalances.

REFERENCES

-
- ¹ Straube, John F. January 2002, "Moisture in Buildings" AHRAE Journal
 - ² Lstiburek, Joseph, February 2002, "Moisture Control in Buildings", ASHRAE Journal
 - ³ Harriman, Lew, Brundrett, Geoff, Kittler, Reinhold, 2001, Humidity Control Design Guide, Chapter 23, ASHRAE
 - ⁴ Harriman, Lew, Brundrett, Geoff, Kittler, Reinhold, 2001, Humidity Control Design Guide, Chapter 11, ASHRAE
 - ⁵ Persily, Andrew, 1998, "Airtightness of Commercial and Institutional Buildings: Blowing Holes in the Myth of Tight Buildings", Conference Proceedings of Thermal Performance of the Exterior Envelopes of Buildings VII, page 829
 - ⁶ Cunningham, James; Withers, Charles; Moyer, Neil; Fairey, Philip; McKendry, Bruce; 1996, "Uncontrolled Air Flow in Non-Residential Buildings"; Contract Report FSEC-CR-878-96; Florida Solar Energy Center

⁷ Browning, B.K., 2002, "Direct Expansion Air Conditioning System Selection for Hot & Humid Climates", Proceedings of the 13th Symposium on Improving Building Systems In Hot & Humid Climates

⁸ Henderson, H. I., 1998, "The Impact of Part-Load Air-Conditioner Operation on Dehumidification Performance: Validating a Latent Capacity Degradation Model", IAQ and Energy Transactions 1998, Pg 115 - 122

⁹ Harriman, Lew, Brundrett, Geoff, Kittler, Reinhold, 2001, Humidity Control Design Guide, Chapter 2, ASHRAE