WHEN YOU NEED TO BE SURE

CyFlex® Knowledge Article

Combustion Air Handler – Steam Addition

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Background

As part of the air handler commissioning process, we attempted to run a test to verify that the unit could achieve the maximum humidity target specified in the design matrix. Steam is delivered to the humidifier through two valves, one large 4” valve, HH*CAU04, and a smaller 2.5” valve, HH*CAU05. When we fully opened the large steam valve, the steam supply pressure dropped rapidly and did not recover. The low-pressure steam boilers could not keep up. We also observed that only a relatively small fraction of the smaller steam valve range was required to achieve nominal humidity values even on days when the ambient humidity was very low. These observations caused us to question whether the steam valves were properly sized.

To determine the steam mass flow rate as a function of valve command, we ran several experiments with the engine running at maximum air flow and the weighted relief damper blocked closed so all the humidified air was forced to go through the air flow meters.

Calculations

Given the measured combustion air mass flow rates and humidity as well as the ambient humidity, we should be able to calculate the mass flow rate of the steam being injected into the air stream. The mass flow rate of water vapor in the wet combustion air stream, $\dot{m}_{h2o,air,wet}$, is the sum of the mass flow rate of injected steam, $\dot{m}_{steam}$, and the mass flow rate of water vapor in the ambient air stream, $\dot{m}_{h2o,air,amb}$.

$$\dot{m}_{h2o,air,wet} = \dot{m}_{steam} + \dot{m}_{h2o,air,amb} \qquad \text{sa.1}$$

The mass flow rate of wet combustion air, $\dot{m}_{air,wet}$, is the sum of the dry air mass flow rate, $\dot{m}_{air,dry}$, and the mass flow rate of water vapor in the wet combustion air.

$$\dot{m}_{air,wet} = \dot{m}_{air,dry} + \dot{m}_{h2o,air,wet} \qquad \text{sa.2}$$

The specific humidity of the wet combustion air, $SH_{air,wet}$, can be defined as the ratio of the mass flow rate of water vapor in the wet combustion air stream to the mass flow rate of dry air.

$$SH_{air,wet} = \frac{\dot{m}_{h2o,air,wet}}{\dot{m}_{air,dry}} \qquad \text{sa.3}$$

If we measure the vapor pressure, $vp_{h2o,air,wet}$, and the absolute static pressure, P_{abs}, at that location, the specific humidity can be calculated using

$$SH_{air,wet} = \frac{\dot{m}_{h2o,air,wet}}{\dot{m}_{air,dry}} = \frac{vp_{h2o,air,wet}}{P_{abs} - vp_{h2o,air,wet}} \frac{M_{h2o}}{M_{air,dry}} \qquad \text{sa.4}$$

The ambient specific humidity can be calculated in a similar fashion

$$SH_{air,wet,amb} = \frac{\dot{m}_{h2o,air,amb}}{\dot{m}_{air,dry}} = \frac{vp_{h2o,air,amb}}{P_{abs,amb} - vp_{h2o,air,amb}} \frac{M_{h2o}}{M_{air,dry}} \qquad \text{sa.5}$$

Because we don't always have a pressure measurement at the location where vapor pressure is measured, we are often forced to make the assumption that the absolute pressure is the barometric pressure, P_{baro}.

Solving the previous two equations for the mass flow rate of water gives

$$\dot{m}_{h2o,air,wet} = \dot{m}_{air,dry} SH_{air,wet} \qquad \text{sa.6}$$

and

$$\dot{m}_{h2o,air,amb} = \dot{m}_{air,dry} SH_{air,wet,amb} \qquad \text{sa.7}$$

Substituting the above into the equation for the mass flow of water vapor and solving for the mass flow rate of steam and collecting terms gives

$$\begin{aligned} \dot{m}_{steam} &= \dot{m}_{h2o,air,wet} - \dot{m}_{h2o,air,amb} \\ &= \dot{m}_{air,dry}\left(SH_{air,wet} - SH_{air,wet,amb}\right) \end{aligned} \qquad \text{sa.8}$$

By making a similar substitution into the equation for the mass flow rate of wet combustion air and solving for the mass flow rate of dry air, we get

$$\left.\begin{aligned} \dot{m}_{air,wet} &= \dot{m}_{air,dry} + \dot{m}_{h2o,air,wet} \\ &= \dot{m}_{air,dry}\left(1 + SH_{air,wet}\right) \end{aligned}\right\} \Rightarrow \quad \dot{m}_{air,dry} = \frac{\dot{m}_{air,wet}}{\left(1 + SH_{air,wet}\right)} \qquad \text{sa.9}$$

Combining the above two equations gives us the desired result

$$\boxed{\dot{m}_{steam} = \dot{m}_{air,wet} \frac{\left(SH_{air,wet} - SH_{air,wet,amb}\right)}{\left(1 + SH_{air,wet}\right)}} \qquad \text{sa.10}$$

Since we seem to have a valve sizing issue, a parameter of interest is the valve flow coefficient, C_v, as a function of valve command. A general formula for the non-critical flow of saturated steam is given by

http://www.engineeringtoolbox.com/flow-coefficients-d_277.html

as

$$\boxed{C_v = \frac{\dot{m}_{steam}}{2.1\left[\left(p_i + p_o\right)\left(p_i - p_o\right)\right]^{1/2}}} \qquad \text{sa.11}$$

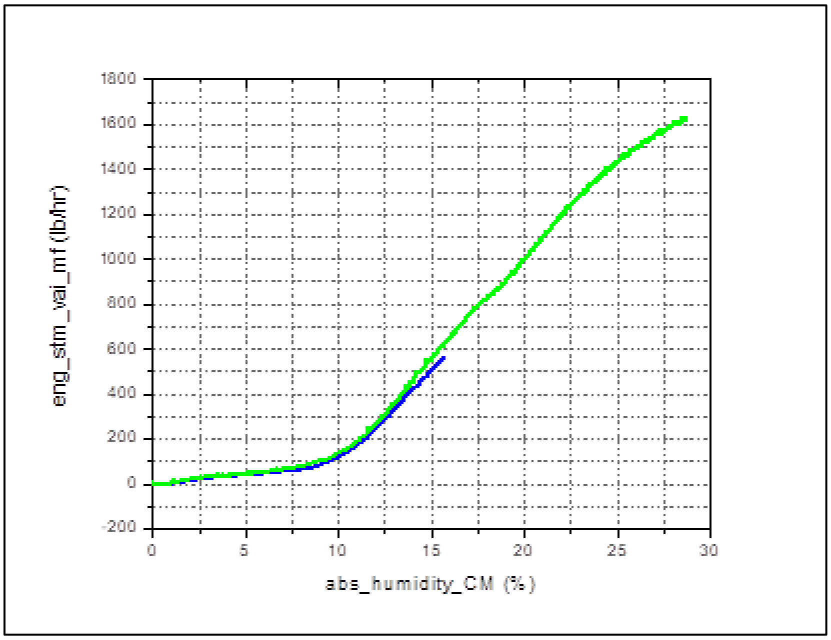
where p_i is the absolute pressure upstream of the valve and p_o is the absolute pressure downstream. The values for both are assumed have units of psia. The steam mass flow rate is assumed to be in lb/hr.

If we are not measuring the downstream pressure, but we think we know C_v based on manufacturers data and we can measure the upstream pressure and mass flow rate, we can calculate the downstream pressure by rearranging the above equation to get

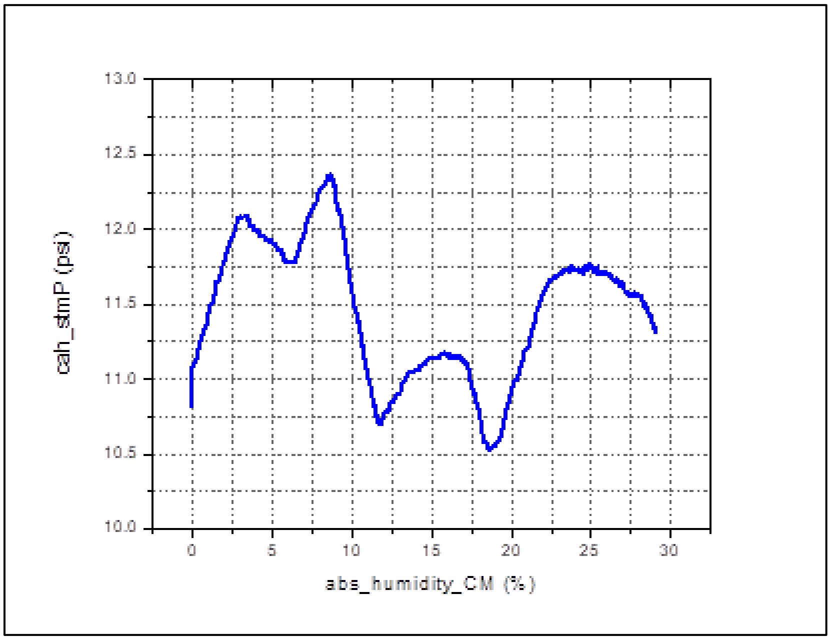
$$\boxed{p_o = \left[p_i^{\,2} - \left(\frac{\dot{m}_{steam}}{2.1C_v} \right)^2 \right]^{\frac{1}{2}}} \qquad \text{sa.12}$$

Experimental Results

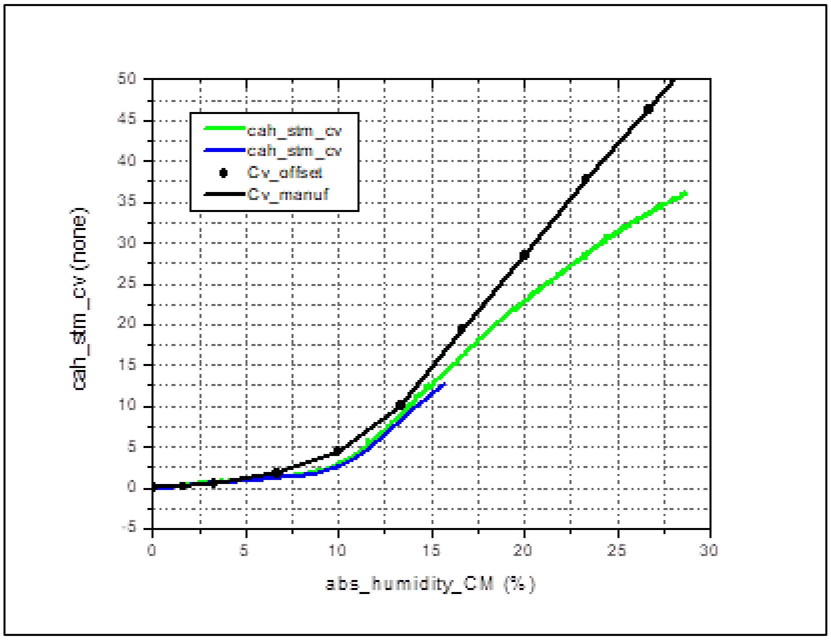
We ran two tests with the engine running rated and the weighted relief dampers blocked closed. The valves are sequenced so that from 0% valve command to 33%, the small valve goes from 0% to 100% open. Both tests had to be shut down due to engine problems before we had a chance to fully open the small valve. The steam mass flow rate for the two tests was calculated using Equation sa.10 and is plotted below vs valve command.



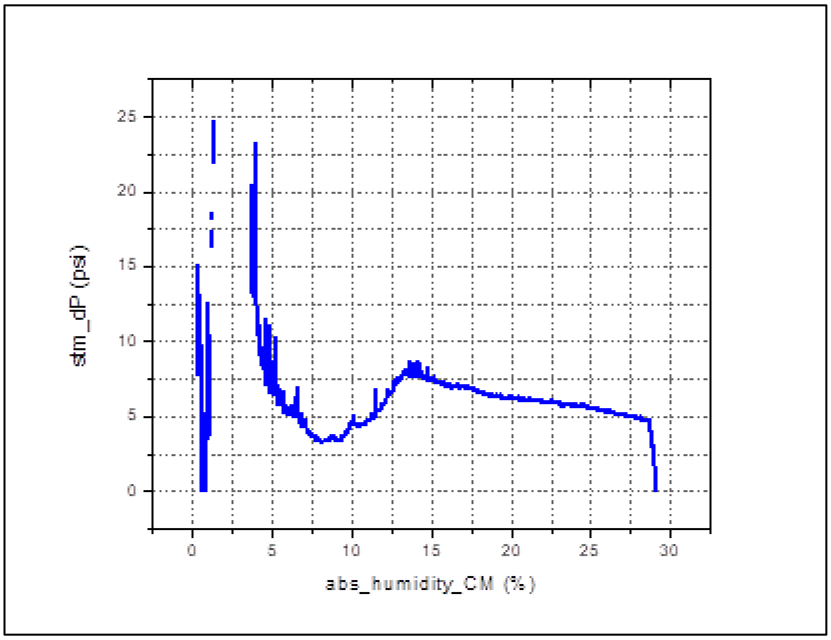
The steam mass flow rate is not solely a function of valve lift – the steam pressure plays an important role and it, unfortunately, was not at all constant during the second (green) test as shown in the plot below.



If we calculate the valve *Cv* and plot that against valve command, it becomes more useful for valve sizing as shown below.



The small valve is a 2.5" Samson model 3241 with equal percentage trim. The black dots on the plot are manufacturers data from Table 3241.21 of Samson document T8000-3 EN which have been offset downward by 2.0 so the valve is shown to be fully closed at 0% command. The *Cv* for the experiment data was calculated using Equation sa.11 based on the assumption that the pressure in the humidifier manifold downstream of the valve was the same as the air pressure at the air handler exit. The data agree fairly well with the manufacturers values at low flows but begin to separate at higher flows. This is not unexpected given that the manifold pressure would naturally increase as the flow rate increases. If we assume the manufacturers Cvs are correct, we can use Equation sa.12 to back-calculate the differential pressure across the valve. The plot below shows the result.



The value of this calculation is somewhat questionable. It obviously blows up under 5% command. The shape of the curve from there to below 15% is hard to explain. Above 15% it seems more reasonable. We need to repeat these tests or add a transducer to measure humidifier manifold pressure to sort this out.

Valve Sizing Calculations

Using the official US EPA Goff saturation curve correlation, the 95 F maximum dewpoint design specification corresponds to a vapor pressure of 1.665 in_hg. Assuming standard atmospheric pressure of 14.696 psi and applying Equation sa.4, this translates to a target specific humidity of 255.8 grains/lb dry air.

The molar mass of wet air at this humidity level would be 28.358 g/mol. The wet air density at standard atmospheric pressure and 77 F would be 0.07236 lb/ft3. So, the mass flow rate of wet air at the maximum design volumetric flow rate of 16,000 cfm would be 1158 lb/min.

If we assume bone dry ambient air and use the above values in Equation sa.10, we find that the required steam mass flow rate is 2449 lb/hr.

If we assume Combining the above two equations gives us the desired result

$$\dot{m}_{steam} = \dot{m}_{air,wet} \frac{\left(SH_{air,wet} - SH_{air,wet,amb}\right)}{\left(1 + SH_{air,wet}\right)} \tag{sa.13}$$