## Problem Statement

All systems in which we are attempting to control the humidity consist of two distinct pieces – the point where water vapor enters the system (the saturator) and the point where we wish to maintain a given (in this case the cell, PAS or CRDS). The latter is downstream of the former and is connected via tubing. **We want to control the cell at a single and maintain a steady value through temperature and pressure perturbations.**

To a good approximation, the relative humidity ( ) at the measurement point (the cell) is a function of the saturation vapor pressure at the saturator () and the saturation vapor pressure of the air in the location of the measurement ().  This relation is simple

The saturation vapor pressure is defined by the *Clausius-Clapeyron* equation:

where is the water vapor gas constant and is the latent heat of evaporation. Due to the temperature dependence of , the equation is implicit and therefore is best defined by one of the parameterizations in the literature. In this case, the parameterization of *Murphy and Koop* [eq. 10; 2005] provides a reasonable solution:

where is in Kelvin and is good in the range of 123 to 332 K.

In theory, the of the cell may be controlled strictly by controlling the saturator temperature. The current system uses a bidirectional thermoelectric cooler to adjust the temperature on the saturator. The TEC uses a heater/cooler that it can drive between approximately V to achieve a consistent temperature based upon an input setpoint. The input is in volts and the voltage can be calculated by converting the desired temperature to a thermistor resistance and dividing by 5000. This resistance is calculated using the characteristics of the thermistor that is used to measure the saturator temperature. This same thermistor used to measure the temperature of the saturator is used by a PID control loop as the process value. The PID control loop is based in hardware and the gains can only be set by swapping out components.

However, given certain potential non-idealities, it is clear from preliminary tests that the saturator does not produce saturated air. The extent to which the air comes out saturated is dependent on several factors including

* the residence time of the air in the saturator (i.e. flow rate)
* initial thermodynamic state of the air entering the system (air temperature and water content)
* inhomogeneities in the saturator temperature (due to incomplete insulation, transient effects, etc)
* gas pressure (affects mass transfer)
* etc., etc

In addition, there may be unaccounted loss mechanisms of water vapor in the system and the placement of the sensors and their relative uncertainties may impact the measurement of pertinent variables.

Given these non-idealities, it is desirable to develop a closed-loop control system to control via heating of an upstream saturator. A PID loop seems a reasonable choice for control and has been used effectively in similar systems. For this particular system, the TEC would be controlled using a software based algorithm written in Labview. The PID output for the Labview algorithm can be defined as

In this case, the error term can be defined as

For the current system in which we wish to control the relative humidity, we have to convert this PID output to a TEC voltage (temperature) input. Using the TEC, we find the following to be true:

Where SP is the setpoint, PV is the process value, T is the temperature setpoint, and V is the voltage setpoint (the latter two are related).

## Now the real problem…

Now the problem lies in how we use the output to drive the temperature of the TEC. The above equation for the controller output suggests that when the error is 0, the output should be 0. In the TEC, the temperature is the end-product of an energy input into the system; that is, we never directly control the temperature but only attempt to achieve a requested temperature through heating or cooling of the saturator block. By controlling the temperature, **there is no point at which we can guarantee that the heater will be off‼** (which we would desire should the approach the setpoint). **In fact, we have no way of reliably accounting for how the controller will react as we attempt to change temperatures as we approach the setpoint.**

Related to this, we have to have a way of solving the following problem:

*As , ; this controller output must be used to drive the process (TEC) input. However, if we use the value , where is a scaling factor, we will drive the TEC input to 0 and therefore request the TEC to apply the maximum amount of heat to the saturator (unacceptable). So, how do we use to drive the saturator output to produce the correct without assuming ideal saturator output (which would imply no need for a closed loop control; i.e. the PID on the TEC is sufficient to achieve the values we require)?*

## What did everyone else do?!

As I state above, our system is similar to others that are already in service. The humidified tandem differential mobility analyzer (HTDMA) is a system that immediately comes to mind. In the HTDMA, air is sampled by a scanning mobility particle sizer (SMPS) which provides a distribution of particles at a fixed rate at the outlet. The output of the SMPS is fed through a saturator and connected to another SMPS which in turn measures the resulting humidified size distribution. In these systems, the saturator is similar to the ones found in the PAS and CRDS. However, they are often heated by heating tape and the PID controller has direct access to the heater (i.e. the control loop has control over how much power is applied to the tape).

## Conclusion

My current thought is that if we get a PID system to work it will be most likely due to dumb luck rather than sound control theory. It is not clear to me how we can close the loop between the output of the PID and the input voltage as there is no clear transform between temperature and other than the ideal one (and in that case we have no need for a closed-loop control system other than the one that controls temperature). I think that if we were to do this effectively, we would need to be able to adjust heater power, not the temperature setpoint, so that we could have a clear controller response that is not convoluted by the response of the TEC control loop.

If there is no way to have direct access to the heater, then I think that there are two potential paths we may take to solve this problem. The first is the simplest and requires the verification of an assumption. That assumption is that the saturator output is most prominently affected by the residence time. In this case, for a given Q, we can hunt for an expected saturator output (i.e. 95%) that might get us to the we desire and then use that empirically determined saturator output to control the through any small temperature oscillations.

However, it is likely that changes in pressure can have a significant impact on the saturator effectiveness. In that case, we can use the ideal approximation of the to get us close to our setpoint and then nudge the controller using small voltage steps and big time steps to get us to the actual value. In this case, it may take a while to get to that setpoint, but, barring any large perturbations, is likely to keep us within the desired control range.