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CPC Topic Sheet:
“Part Temperature Control”

ASC Process Systems, Inc.

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General

This topic sheet discusses the functionality, capabilities, and how-to of recipe programming and part temperature control in a typical CPC-controlled autoclave application.

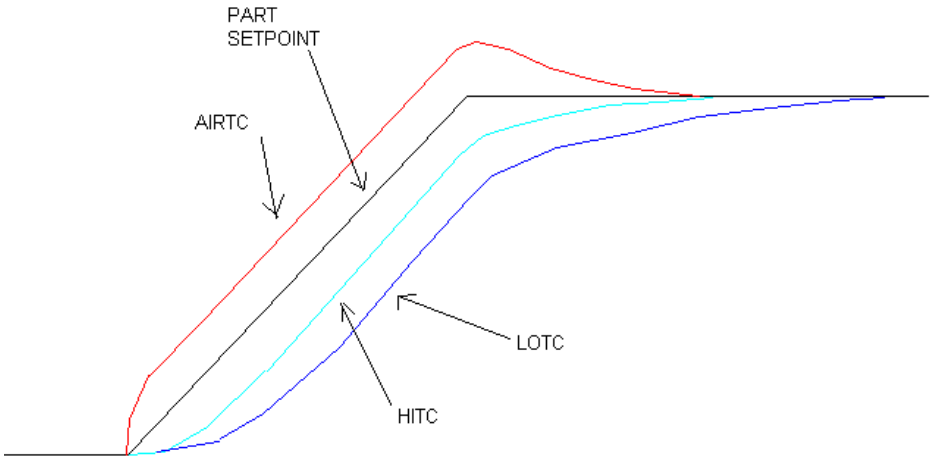
Part temperature control

CPC utilizes multiple internal settings and functions to achieve “part temperature control”. The settings are made in the CPC Recipe and include the following function sets:

1. Cascade Control with Integral
2. Part Spread control
3. Part Rate control
4. Air to Part Spread Control
5. Max Air Temp Control

Cascade Control

Cascade Control is a method of control where various control units are linked in sequence, each control unit regulating the operation of the next control unit in line. In the case of an autoclave, the multiple control units are air temperature and part temperature.



In CPC Cascade Control, the system proportionally sets an air-temperature setpoint based on the deviation of the part temperature from the part temperature setpoint.

Cascade control function is setup in the CPC’s recipe with the following parameters:

1. Control_TC
2. Temperature_Rate

3. Temperature_Value
4. Cascade_IN
5. Cascade_OUT
6. Add_Per_Time

Control TC

The control thermocouple is the actual thermocouple input value or derived temperature input value that will be the source variable for the part controller. Although you can target a specific part temperature (ie. PTC5), ASC strongly recommends the use of the derived input HITC during heating and LOTC during cooling so that you are controlling the outside limiting thermocouple.

HITC – HITC is the highest reading part thermocouple currently active and not disabled in the run.

LOTC – LOTC is the lowest reading part thermocouple currently active and not disabled in the run.

Temperature Rate and Value

The Rate and Value entry indicate the target for the Control TC entry. For example, if you want the HITC to heat at 4 degF/min to a goal of 350 deg.F, then the entry would be:

Control_TC: HITC

Temperature_Rate: 4

Temperature_Value: 350

Part and Air Setpoints defined

The PartSetpoint is the theoretical target setpoint for the part controller. This setpoint will change based on the Rate and Value entry above. During a heat segment, the part setpoint will ramp up at the programmed Temperature_Rate and stabilize at the goal temperature set by Temperature_Value.

During a part-controlled recipe cycle, the actual part temperature being controlled (ie. HITC) will achieve a heating rate which closely matches the part setpoint rate, however in doing so the part temperature will remain below the part setpoint.

During a part-controlled heating cycle, the air temperature setpoint will be set at a pre-calculated value above the part setpoint in order to drive the part temperature properly. The Air Setpoint calculation is a function of the Cascade Controller within CPC.

Air setpoint calculation

The cascade function utilizes the following calculation to create an air temperature setpoint:

S = *(PartSetpoint – PartTemp) x (CascadeOUT / CascadeIN)*

If S > CascadeOUT, then S = CascadeOUT

Air Setpoint = PartSetpoint + S

As you can see, the ratio of CascadeOUT to CascadeIN determines the overshoot that the air temperature is set to. Additionally, the CascadeOUT parameter is a limiter to the amount of overshoot.

In practice at the beginning of a heating cycle, the PartSetpoint-to-PartTemp deviation will begin to grow and the cascade function will immediately respond with a higher and higher overshoot of the air temperature setpont. As the part temperature begins to heat, the increase of the deviation will subside until finally the part temperature is heating at the same rate as the part setpoint. At this point, the cascade controller will achieve a steady-state condition and the air-temperature will be ramping at the same rate as the part temperature.

Add Per Time integral function

Because cascade control works proportionally from the deviation of part temperature to part setpoint, there is a possibility that in a non-uniform autoclave the part temperature will never get to final part setpoint. In this case, the part temperature remains a few degrees below setpoint and the air temperature (Cascaded) remains a few degrees above. In this case, the programmer can utilize “Add Per Time” parameter to create an integral function which bumps the air-temperature until the deviation is eliminated.

Add Per Time is entered in units = deg.F Add / deg.F Deviation / Min. Practically, AddPerTime slowly increases air temperature based on the amount of part temperature deviation over time.

For example, if AddPerTime is set to **.2** (deg.F/deg.F/min) and the part temperature is deviating 10 deg.F from setpoint, then the system will add **.2** x 10 = 2 deg.F/min to the air temperature. As the air temperature increases, the deviation will decrease and the resultant function will slowly decrease. For instance, if the deviation decreases to .1, then the system will be adding 1 deg.F/min to the air temperature. When the deviation reduces to zero, nothing more will be added.

It is very important to not use too high a value in the AddPerTime variable due to possible instability that can occur. It is also important to only enable Add Per Time in the recipe only once the control thermocouple is near the final target temperature. If for example Add Per Time is enabled during ramping, then the system will exceed the selected programmed rate.

Do cascades have an effect on part rate?

Because CPC’s cascade controller reacts to the deviation of the part temperature to the ramping or steady part setpoint, it is actually not a part rate controller. Nevertheless, due to its inherent ability to force the part temperature to mirror the part setpoint rate, it does ultimately control the part rate.

In cases where a customer requires active part rate control, ASC has implemented a new Part Rate Controller feature.

Is the ramping and cascades effected by MaxPartRate or MinPartRate?

The answer is NO. The MaxPartRate and MinPartRate parameters define alarm limits only. They do not play a part in control. The system will allow you the freedom to request a programmed ramp rate which conflicts with these alarm values.

Can cascade function control HITC and LOTC simultaneously?

The answer is NO. Because ultimately the system is controlling air temperature and the part temperature is heating (or cooling) based on the physical heat transfer to the air, the cascade controller can really only “control” the behavior of one temperature value at a time. The Control_TC parameter dictates the actual controlled value, and you are free to change that value segment by segment to your liking.

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ASC almost always recommends control by HITC and not LOTC. If you control the ramp rate by LOTC or AVGTC or some other similar value, then it is likely that some of the part thermocouples will exceed the upper specification limit.

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Part and load spread control

The CPC recipe system includes a unique function that controls the spread between highest and lowest thermocouple on any part or the load. This function is called “spread control” and is configured and programmed at the recipe level.

Recipe parameters

Although each customer system can be configured different, the following basic parameters are included in the Recipe for spread alarming and spread controlling.

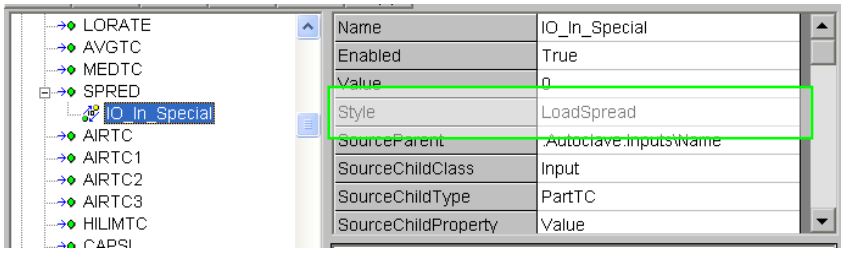
Max_Part_Spread – Temperature limit in Deg.F (or C)

Grace_Period - Time grace period for alarm

Control – This is a ON or OFF entry indicating that you want spread to be controlled.

SPRED input

Before a system can control spread, a CPC input must be configured to categorize and calculate the current spread. *The input is usually named SPRED, PSPRED, LSPRED or something similar.*



The input includes an IO_In_Special child object that defines the **Type** of spread being calculated. The options for spread are LoadSpread or PartSpread.

LoadSpread – For this type, the system calculates spread by calculating the instantaneous absolute difference HITC and LOTC. This represents the temperature gradient of all active part thermocouples.

PartSpread – For this type, the system calculates the individual temperature gradient for every single part based on its active thermocouples. After analysis, the SPRED input shows the maximum gradient of the parts analyzed.

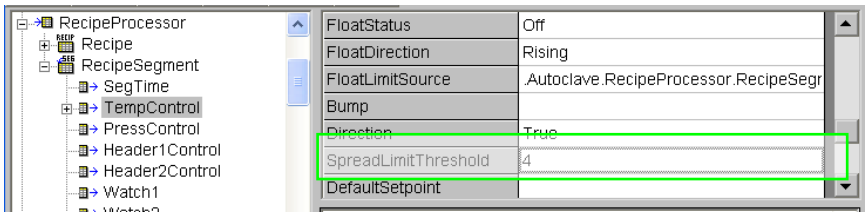
Spread limiting threshold

A key parameter used by the spread controller is the “SpreadLimitThreshold”. This parameter is the threshold around the limit that triggers the start of spread control.

When the system is controlling spread, there is usually no need to perform any corrective control until the spread comes close to the limit defined in Max_Part_Spread parameter. The definition of “close” is set by this threshold value. For example, if you only want the system to begin corrective control when the actual spread reaches within 4 degrees of the limit, then the threshold would be set to 4 (see below).

If the threshold is too large, then the system will be overly conservative and will cutback the part temperature rate too aggressively. ASC recommends an “initial try” value between 2-5 degrees.

Note: If the threshold is blank, then the system creates an automatic threshold which is ½ the current limit. For example, if the limit is 20 degrees, then the system will begin active control at 10 degree spread.



How spread control works

Spread controller works during a heating or cooling segment and lowers the actual part setpoint ramp rate in order to reduce the spread.

During a spread controlled segment, the system tracks the SPRED input and based on a comparison between the current spread value and the alarm limit value, the ramp rate of the part setpoint is reduced.

The overall reduction in the part ramp rate is proportional to approach distance between the actual spread and the current limit.

The following calculation is performed:

PR = Part Setpoint Ramp Rate as set by “Rate” parameter in recipe.
MR = Modified ramp rate based on spread controller output
TS = Threshold temperature (see above)
SL = Spread limit as set by Max_Part_Spread parameter
AS = Actual spread as calculated by SPRED input.
DV = Spread limit minus actual spread.
CC = Corrective control parameter in recipe (“Control”) – ON or OFF

```
If CC = ON and SL > 0 then
        DV = SL – AS
        If DV < TS then
                MR = PR x DV / TS
                If MR < .1 then MR = .1
        Else
                MR = PR
        End if
Else
        MR = PR
End if
```

The calculation above takes the following action:

- The spread control only occurs if Max_Part_Spread is positive value and Control is set to ON in the recipe.
- Spread control only occurs if the actual spread is greater than the (spread limit – threshold).
- The amount of reduction in the part ramp rate is proportional to the ratio of spread-to-limit deviation and the threshold. In practice, this means that if the ramp rate is 5 deg/min and the threshold is 4 deg.f and the actual spread is 3 deg. from the limit, then the ramp rate will be multipled by .75 for a 25% reduction (5 x .75 = 3.75). If later the spread still increases and is only 1 deg. from the limit, then the new ramp rate will be ¼ x 5 = 1.25.

Which happen first – cascade control or part spread control?

Within the software, the spread controller operates before the cascade controller function. Here is the sequence:

1. System determines the ramp rate and target based on recipe Rate and Value parameters.
2. System modifies the ramp rate based on spread control
3. System calculates a new part setpoint based on the current, modified ramp rate.
4. System calculates air temperature based on cascade parameters.

Important things to remember

Prior to using the spread controller function, it is important to realize the following:

- The part spread controller takes priority over cascade and ramp rate settings. This means that if you ask for limiting control, the system might dramatically reduce the rate to achieve spread limiting. For this reason, be sure that spread control is of utmost importance before using it.
- The setting of the Threshold property is very important. If it remains blank, then the system will utilize a threshold which is ½ of the current limit. In most cases, the ½ value is too high for the threshold and will result in a an overly aggressive reduction in the ramp rate. If you plan on using the spread control function, make sure that the threshold is preset to a value in the range of 2-5 degrees.

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Part Rate Controller

The purpose of the Part Rate Control function is to augment the normal Cascade Control algorithm and provide a means of addressing part thermocouple rate anomalies by utilizing active, rate feedback control.

This function is meant to address the situations where Cascade Control does not adequately control the rate of a part, including situations where temperature rate is affected by autoclave pressure or exothermic conditions in the part.

Cascade control refresher

In a typical cascade controlled run, the controlled part thermocouple (ie. HITC) is driven by air temperature to match the slope of the part setpoint line. In a cascade controlled run the part thermocouple eventually heats at the same rate as the setpoint. Recall that the cascade algorithm sets the air temperature above the part setpoint based on a proportion of the deviation that the controlled thermocouple is below the part setpoint line.

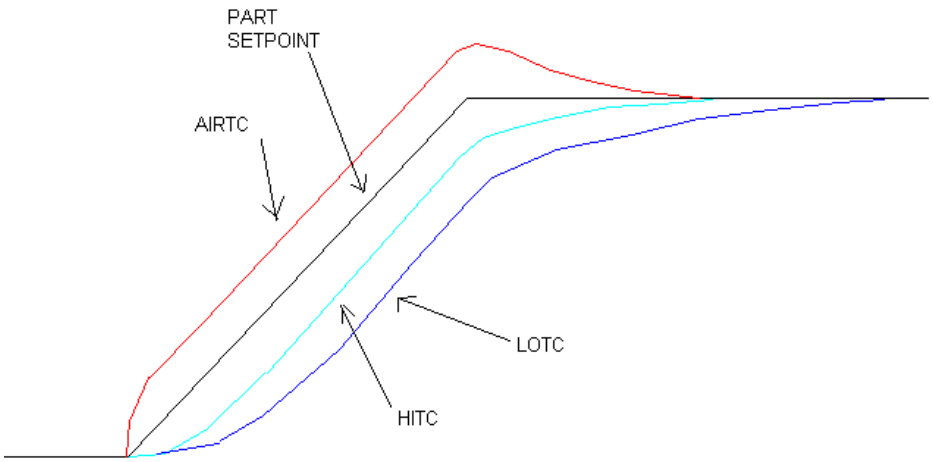
For a HITC controlled run, here is the cascade algorithm:

AirSet = PartSet + OverDrive

Where OverDrive = (PartSet – HiTC)*CascadeOut/CascadeIn.

Note: If OverDrive is greater than CascadeOut, then OverDrive = CascadeOut.

Then



Cascade control responds to the difference between the controlling thermocouple (ie. HITC) and the part setpoint. You can see that Cascade Control does in fact respond to rate changes because were the HITC to heat faster then the part setpoint, then the deviation between part setpoint and HITC would decrease causing the Air Setpoint to decrease.

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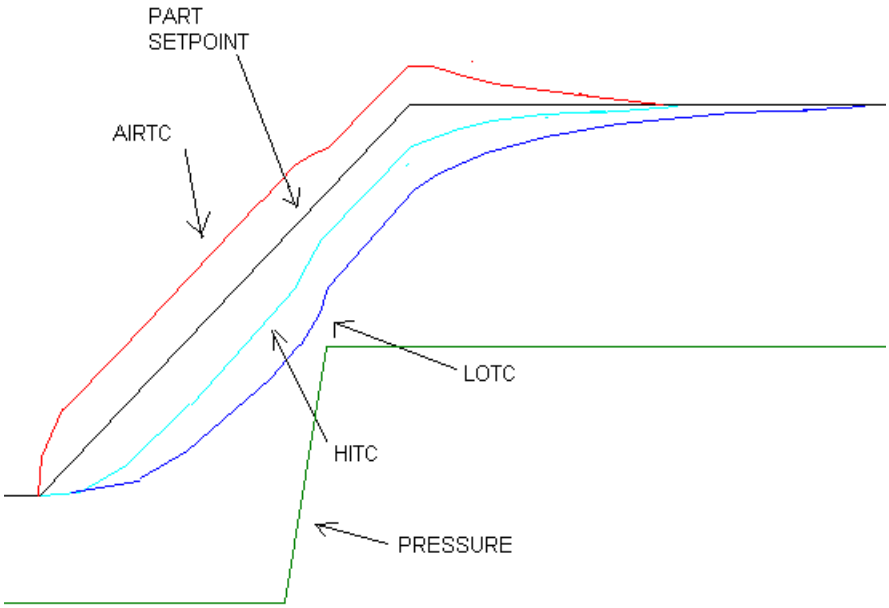
Rate Anomalies

Although in the vast majority of cases the Cascade Control algorithm on its own handles the typical temperature and rate fluctuations that can occur during a run, there are some instantaneous rate change conditions that the Cascade functionality cannot adequately control.

One such condition is shown below. In this case you see that in the middle of the temperature ramp, pressure is applied to the autoclave. Because the internal autoclave gas density increases with more pressure, there is also a natural increase in the heat transfer to the part and therefore a resultant increase in the heat rate of the part. Because the Cascade function is typically only acting on the deviation of part thermocouple to part setpoint, the cascaded air temperature reduces much too slowly to affect a recovery of the rate increase and there is a short period where the part temperature rate exceeds programmed rate.



It is this condition above that has facilitated the development and addition of a secondary Rate Control Algorithm in CPC.

Rate-control principle

The new Rate Control algorithm functions according to the following principle:

"If the highest part thermocouple rate exceeds the target maximum rate, then react immediately by reducing the part setpoint rate which will immediately and dramatically reduce the air temperature, resulting in less heat transfer and a corrected part rate.

The algorithm

The following rate-control algorithm is incorporated:

ACT = Real-time actual highest rate for any active part thermocouple
PR = Programmed rate from the Recipe in deg./min
PSR = Resultant/corrected rate for the part setpoint in deg./min)
FAC = Rate-control factor (ie. 1,2,3 etc.)
THR = Rate control threshold, in % (property setting)
LLM = Low-limit in % (property setting)

if ACT > PR * THR, then start rate-control adjustments....

PSR = PR - (ACT – PR x THR) x FAC

If PSR < PR x LLM then

PSR = PR x LLM

End If

Else If ACT <= PR * THR, then

Allow normal control and take no action.

End if

Rate reduction factor

In practice the Rate Control algorithm reduces the part setpoint rate by a factor which is proportional to the amount that the actual part thermocouple rate exceeds the target rate. For example, if we want the part setpoint rate to reduce from 5 F/min to 4 F/min when the part thermocouple rate climbs from 5 f/min to 6 f/min, then that would indicate a 1:1 reduction or a rate control factor (FAC) of 1.

If we want the reduction to be more dramatic, then we can increase the factor to 2 or 3. A factor of 3 would change the part setpont rate 3x the amount that the part rate exceeds the target rate. For example, with a factor of 3, if the part rate climbs from 5.0 to 5.1 (.1 increase), then the part setpoint rate would decrease from 5.0 to 4.7 (3x or -.3 reduction)

Correcting early – the conservative approach

For the purpose of making corrective changes to the part setpoint, there might be a need to set the target rate at a level slightly less then the controlled rate. In this way you will be assuring that the corrective rate control is fully active prior to exceeding the controlled rate target. This is a conservative approach that should keep the part rate from exceeding the programmed rate. Note: the rate-control threshold property (THR above) is used to set this starting point.

For example, if your part specification max rate is 5 F/min and you are controlling in the recipe to 4.5 f/min, then you might want to start correcting the rate when the part TC rate exceeds 95% of the controlled rate. In this case, THR would be set to 95 and rate control would become active when the thermocouple rate exceeds 4.5 x .95 = 4.05 deg/min.

Don't over-correct

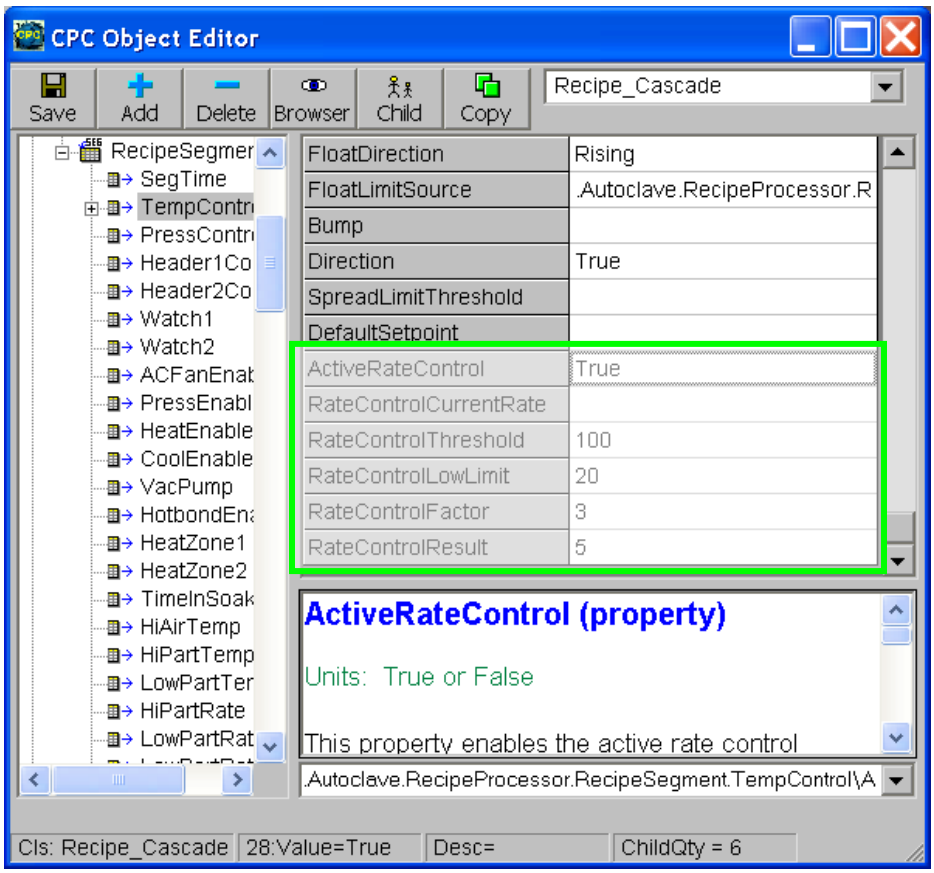
With any algorithm, there is a possibility of over-correcting. The rate-control algorithm has a property called LowLimit (LLM above) which limits the reduction to a fixed percentage of the programmed rate. This is important so you don't completely stop heating when a rate deviation occurs.

The LLM property is a % of programmed rate, so if you set it for 20% then it will indicate that the lowest resultant rate would be 20% of the programmed rate. For example, if the programmed rate is 5 f/min and you don't want the resultant rate to any lower than 1 f/min, then a 20% low-limit would be adequate.

Rate Control Setup

The rate control functionality is programmed with 5 parameters in the Recipe_Cascade object named "TempControl". This object can be located in the object editor with the path:

Autoclave->RecipeProcessor->RecipeSegment->TempControl.



Rate control properties

The following properties are used to define and setup the rate control functionality.

ActiveRateControl - The True/False property enables or disables the active rate control. In most cases this can remain True for active always. *Recall that rate control doesn't actually take hold until the highest thermocouple rate exceeds the programmed rate x THR (threshold).*

RateControlCurrentRate - This property is set by the system and indicates the current highest rate which will be used as feedback for the RateControl algorithm. The system looks at all active inputs with Type = "PartTC".

RateControlThreshold - This % property (THR above) is the threshold above which the rate-control algorithm is enabled. For example, if you set this for 90% and the programmed rate is 5 F/min, then the rate-control algorithm start when actual rate exceeds 5 x .9 = 4.5 f/min. *ASC recommends 95% or 100%.*

RateControlLowLimit - This % property (LLM above) is the lowest resultant setpoint rate that will be adjusted. If for example the low-limit is adjusted to 20% and the programmed rate is 5 F/min, then the rate-control algorithm would only adjust the setpoint rate down to 5 x .2 = 1 f/min. *ASC recommends 20%.*

RateControlFactor - This unitless property (FAC above) is the amount of resulting adjustment that will occur when the part rate exceeds the threshold target. A factor of 1 will result in a 1:1 change in the part setpoint rate. *ASC recommends a factor 2 or 3.*

RateControlResult - This property is set by the system to indicate the current Part Setpoint Rate that is being set. If rate-control is not functional, then this property will indicate the programmed rate. During rate-control, this property will display the actual corrected rate.

When does the rate controller function?

The rate controller calculates it function immediately after the spread controller finishes it's calculations. This means that if the spread controller and rate controller are engaged simultaneously, there might be two corrections to the ramp rate prior to the cascade function calculation.

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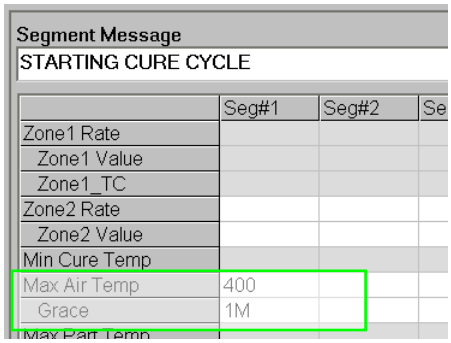
Air temperature limiting

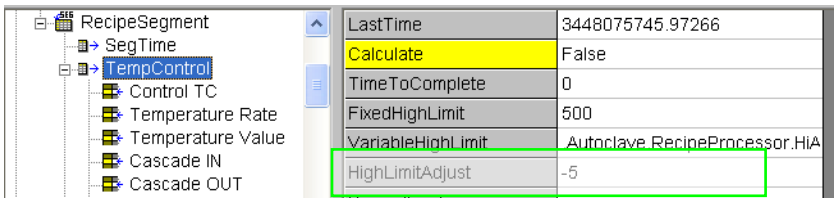
After the Cascade controller calculates and creates it's desired air temperature setpoint, the software tests the air temperature setpoint value through multiple limiters.

Programmable setpoint limiter in Recipe

The Recipe program includes a Max_Air_Temp parameter that is used as a limiter on cascade results. This is often used as the bagging temperature limit.



Note: The system automatically reduces this limiter by an adjustment factor set in the HighLimit Adjust property of the TempControl object under the RecipeProcessor-RecipeSegment object. This adjustment factor is usually set to -5 which results in a reduction of the MaxAirTemp limiter by 5 deg.F



Fixed setpoint limiter in Recipe

The TempControl object includes a fixed high limit value that will limit the air-temperature setpoint at the recipe level. This is usually the same as the Output limiter (see next page).

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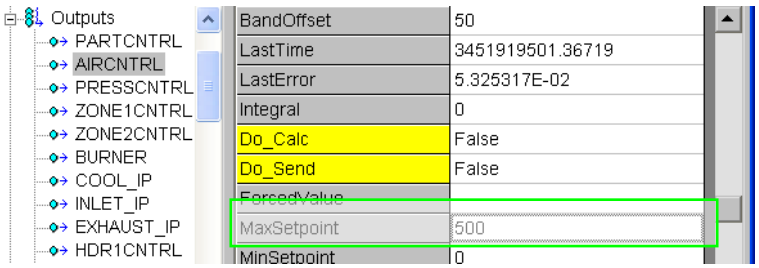
Fixed setpoint limiter in PID output

The output labeled “AIRCNTRL” includes a parameter called “MaxSetpoint”. This parameter restricts the air-temperature setpoint at the actual PID controller. This limiter works in AUTO or SemiAuto control modes.



Air to part delta limiting

Some systems include additional parameters that provide limiting of air temperature based on deviation or gradient from the HITC or LOTC. This is on a case by case basis and can be added to any system easily.

This limiter and alarm parameter is usually named “Max_Air_Part_Delta” and is included in the recipe.

HITC or LOTC comparison

Depending on the system, ASC’s field engineer will configure this parameter to be alarm-only, or alarm and limiter. In the latter case, the engineer will determine which calculated temperature to be used for the limt.

HITC – If HITC is selected, then the air temperature setpoint will be limited to HITC + Delta value. For example, if the HITC = 230 deg. and the delta limiter is set to 50 deg., then the maximum air temperature setpoint will be 280 deg. This will override the cascade results but will not override the MaxAirTemp limiters.

LOTC – If LOTC is configured, then the air temperature setpoint will be limited to LOTC + Delta value. For example, if the HITC = 230 deg. and the delta limiter is set to 50 deg., then the maximum air temperature setpoint will be 280 deg. This will override the cascade results but will not override the MaxAirTemp limiters.