Gooiland 8, 1948 RC
Beverwijk, The Netherlands

Tel +31 0251 27 99 00
Fax +31 0251 21 23 82
email@vtk.nl
www.vtk.nl

Development of anti-surge control system; rev. 7; 2017-08-14

Content

1 Nomenclature

Symbol	Unit	Description
T_{in}	K	temperature at blower inlet
T_{out}	K	temperature at blower outlet
p_{in}	Pa(a)	absolute pressure at blower inlet
p_{out}	Pa(a)	absolute pressure at blower outlet
Δp	Pa	pressure differential across blower
qv_{in}	Am^3/h	volumetric flow rate at suction
qv_{out}	Am^3/h	volumetric flow rate at discharge
ρ_{in}	kg/m^3	gas density at blower inlet
M_{gas}	kg/mole	molar mass of gas
SLV1; SLV2; SLV3	m^4	surge limit value
R	m^4	ASC control parameter
DEV	-	PI-control parameter
n	-	exponent for PI-control parameter
A	-	constant for PI-control parameter

2 Introduction

Project 16.0078 includes the delivery of a blower with anti-surge control system. The goal here is to develop, build and test such system. The anti-surge system comprises a bypass valve which will open if the operating point shifts too close to the top of the fan curve. Opening of the bypass valve has several effects:

- It increases the total flow through the fan and reduces the fan pressure, so that the operating point shifts away from the top of the fan curve. The power consumption of the fan also increases.
- The lower fan pressure makes the flow through the system drop a little. See below figure.
- For 16.0078, the gas through the blow off valve will not be vented to the atmosphere, but recirculated to the inlet of the blower. Some active cooling will be necessary to prevent overheating. A maximum allowable gas temperature should be set and guarded by means of a temperature transmitter.

The purpose of the anti-surge system is to guarantee more stable and reliable operation. The system may be dedicated to the specific blower for 16.0078, but must be universally applicable to centrifugal fans and blowers. Control of the bypass valve should obviously not cause instable operating conditions itself (e.g. as result of poor flow measurements, oscillation of the bypass valve, or cycling into and out of the surge area), while leaving large enough working area of the blower. The system is backed-up by bearing vibration measurements .

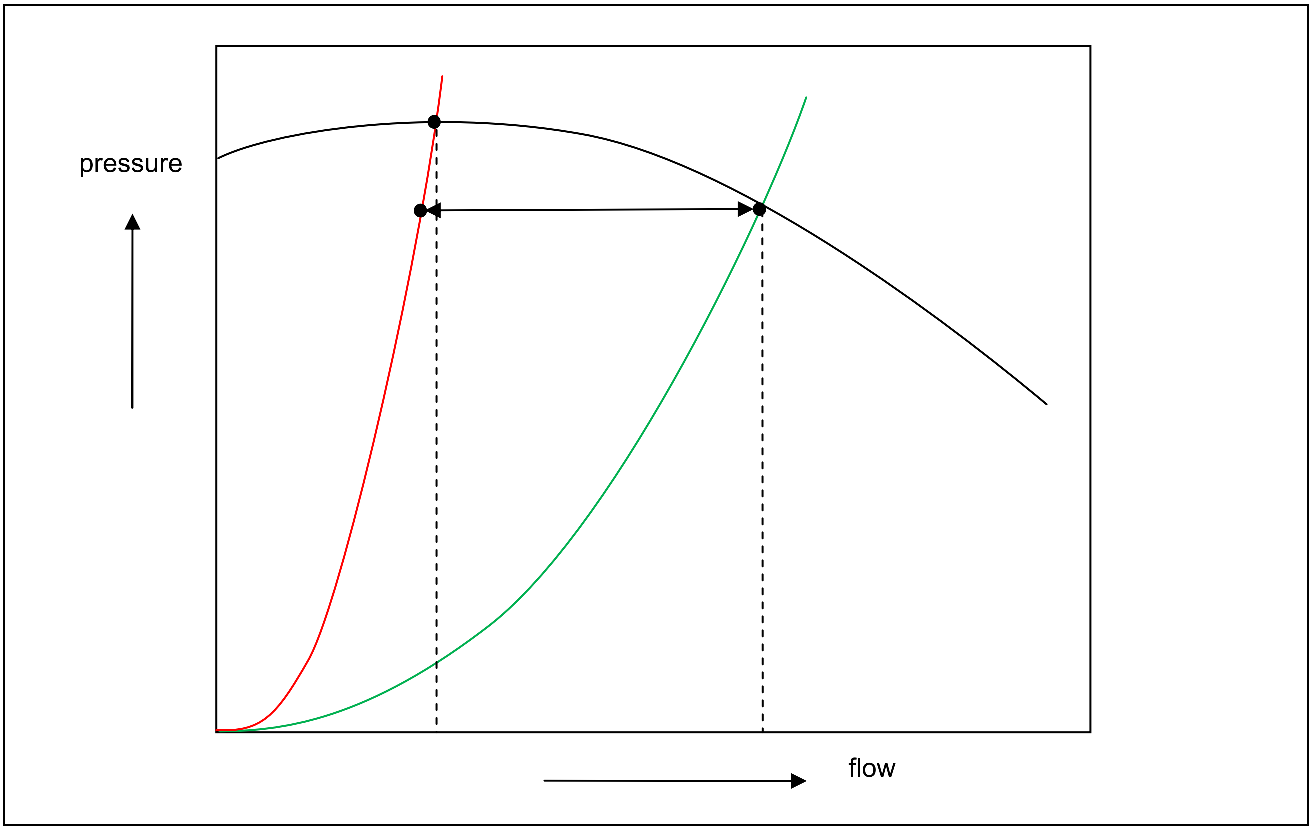

Figure 1: Performance curve with two system curves (green and red). The red system curve yields insufficient flow which is at the critical point for surging. The arrow indicates the required flow through the bypass valve.

3 Process set-up with blower and instruments

Figure 2 shows a simplified P&ID of the anti-surge control system, with blower, temperature transmitters, pressure transmitters, flow meter and bypass valve. The flow rate can be measured in various ways. Influences of gas density and rotating speed of the blower are eliminated through the use of appropriate working equations, provided that flow is measured such that the signal is proportional to the dynamic pressure, i.e. by means of pitot tubes or by pressure drops in systems of known flow resistances such as venturis or orifices. See next paragraph.

The blower will normally start up and shut down against a closed inlet valve or outlet valve (not shown in Figure 2). Table 1 presents start up and shut down sequences. The ASC will be on during the complete sequence. It will open the bypass valve depending on the gas flow rate.

It should be possible to bypass (or switch off) the anti-surge control loop and set the position of the bypass valve manually.

Table 1: Description of blower start up and shut down sequences.

	Description of start up sequence	**Instrument**		
		From	**To**	**Signal**
1	Close inlet valve HV-8653	DCS	HY-8653	20mA
2	Close block valve at discharge			
3	ASC must be on. ASC will open bypass valve and generate low flow alarm	ASC	FY-5542	4mA
4	Check permissives	DCS		
5	Start E-motor of blower	DCS		
6	Wait until motor speed exceeds minimum rpm	DCS		
7	Open inlet valve HV-8653 (1 minute)	DCS	HY-8653	
8	Open block valve at discharge (speed depending on pressure differential)			

	Description of shut down sequence	**Instrument**		
		From	**To**	**Signal**
1	Close inlet valve HV-8653 (0.5 minute)	DCS	HY-8653	20mA
2	ASC will open recycle valve FV-5542 and will generate a low flow alarm	ASC	FY-5542	
3	Stop E-motor of blower	DCS		

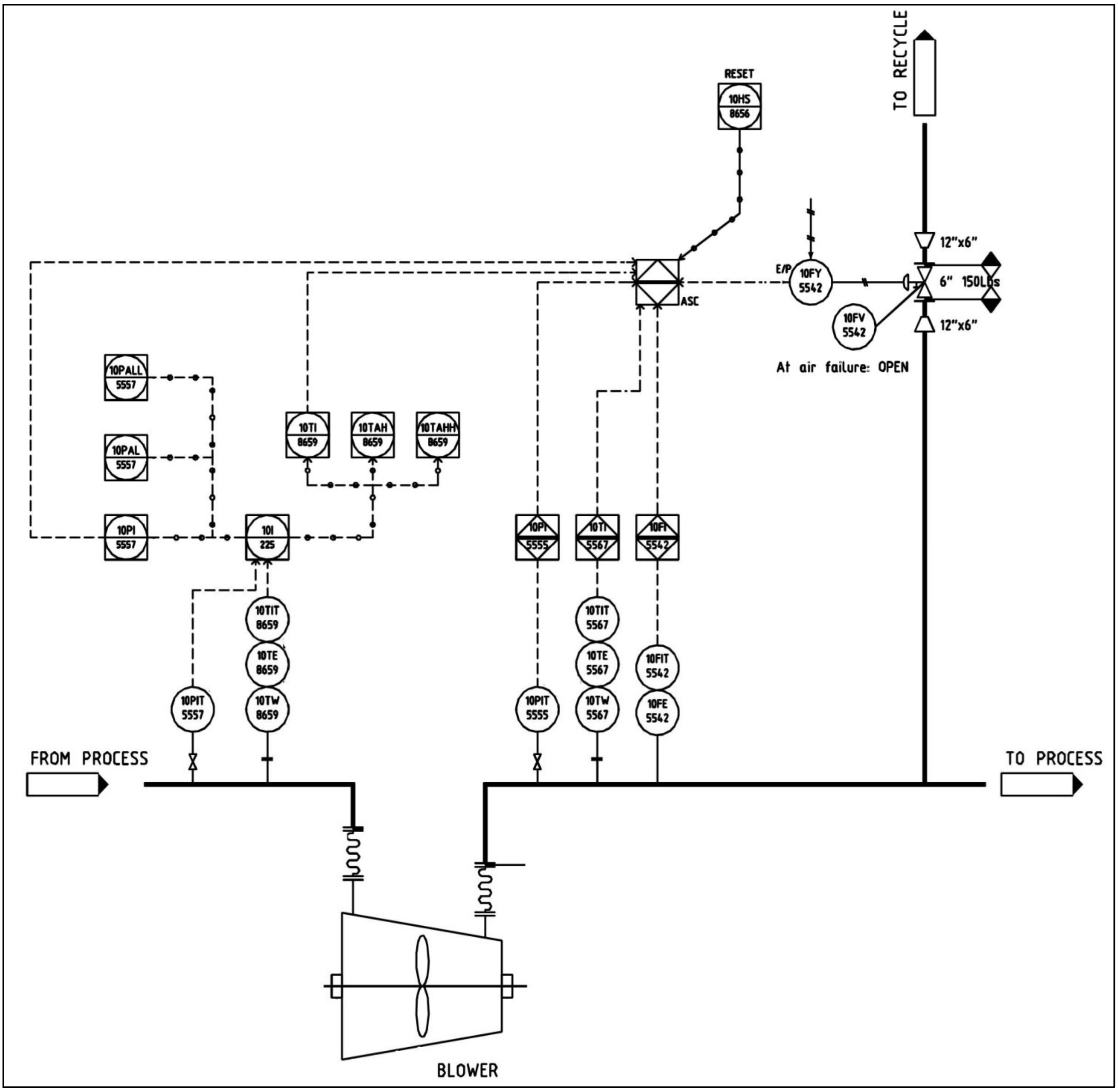

Figure 2: Simplified P&ID of the anti-surge control system. A gas cooler and a vessel with volume of approx. 10m3 are present downstream the recycle valve.

4 Definition of control parameters

The surge limit value SLV1 is a set point for the anti surge controller (by authorized personnel only). It relates to the flow rate below which the blower starts to surge. The surge limit value for the ASC system is defined as $\rho^0_{in} \cdot qv^0_{in}{}^2/\Delta p^0$, with ρ^0_{in} denoting the density at blower inlet, qv^0_{in} the volumetric flow rate at blower inlet and Δp^0 the static pressure differential across the blower, all at the critical point for surging. The reason for using such definition is the quotient's independency of the inlet gas density and of the rotating speed of the blower when using an orifice flow meter to determine the numerator $\rho^0_{in} \cdot qv^0_{in}{}^2$.

The theoretical value of SLV1 was derived from the blower curve at normal design conditions. See Table 2.

For this project, flow will be measured at the blower's discharge and converted to suction conditions by the anti-surge controller. The working equation for the primary control parameter is as follows:

$$R = \frac{\rho_{in} \cdot qv_{in}^2}{\Delta p} = \frac{1}{\Delta p} \cdot \frac{M_{gas} \cdot p_{in}}{8.31 \cdot (T_{in} + 273.14)} \cdot \left(qv_{out} \cdot \frac{p_{out}}{p_{in}} \cdot \frac{T_{in}}{T_{out}} \right)^2 \qquad [1]$$

Table 2: Parameters at the surge limit value SLV1 for the blower of 16.0078.

Parameter	Symbol	Unit	Value at surge limit
Mass flow	q_m	kg/h	17800
Density at suction	ρ_{in}	kg/m^3	4.145
Volume flow at suction	qv_{in}	m^3/h	4294
Blower diff. pressure	Δp	bar	1.834
Surge limit value	SLV1	m^4	416.8

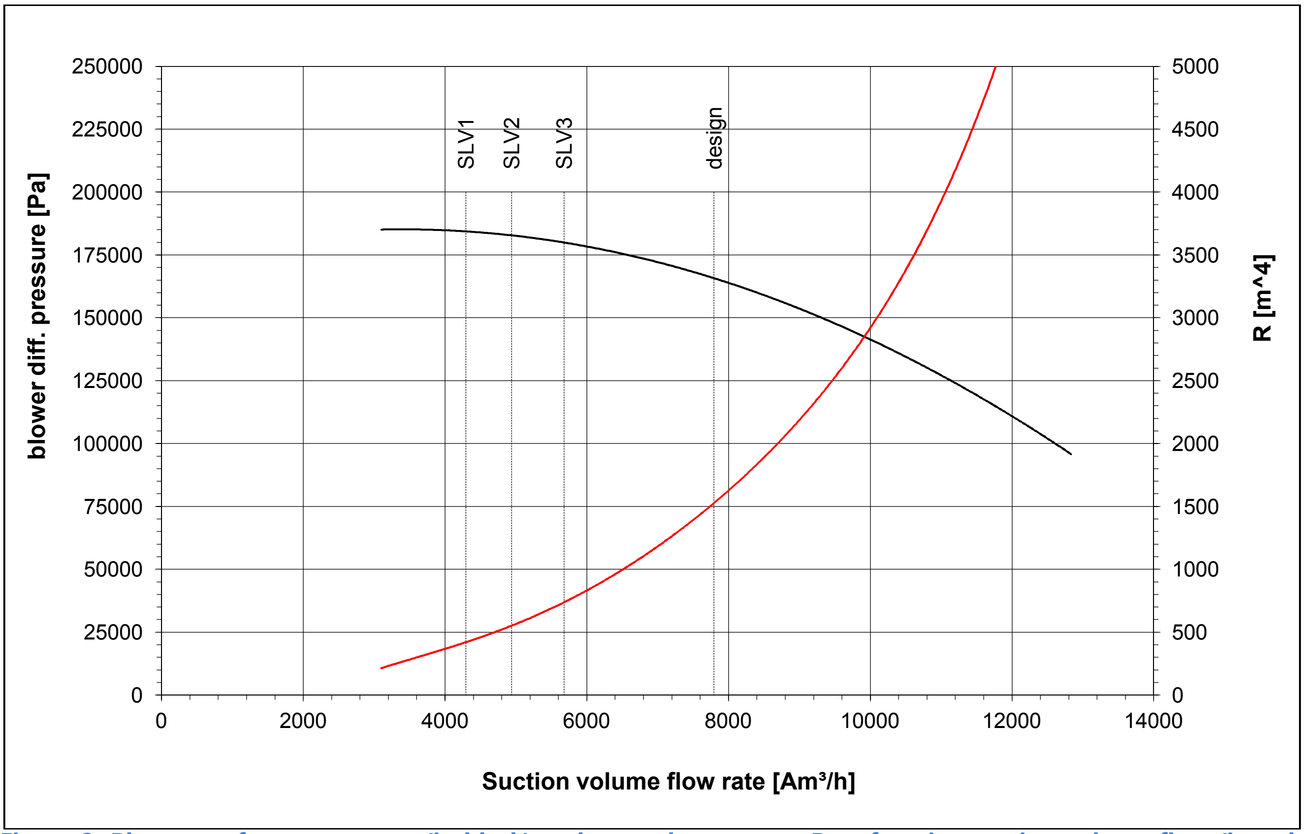

Figure 3: Blower performance curve (in black) and control parameter R as function suction volume flow (in red, along secondary axis). Values of Margin1 and Margin2 are 15%.

The graph of Figure 3 presents the blower curve and the parameter R as function of the volume flow at blower inlet. The surge limit SLV1 has been indicated in the graph, as well as two other limits, named SLV2 and SLV3. They are defined by equations 2 and 3:

$$SLV2 = SLV1 \cdot (1+Margin1) \qquad [2]$$

$$SLV3 = SLV2 \cdot (1+Margin2) \qquad [3]$$

The response of the ASC system depends on the value of R in relation to SLV1, SLV2 and SLV3. The normal operating point is at the right side of SLV3 in Figure 3 (the design point). Now, assume that the operating point tends to move towards SLV1 because of an increase in the system's resistance. In that case, the bypass valve should open when the operating point passes SLV3, which is at some safety distance to the right of SLV1. The response should be such that the operating point shifts back to SLV3. However, if the ASC response is too slow, the operating point may move further to the left for some period, and may in fact pass SLV2. In that case, the bypass valve position should turn to a preset safety value (to the right of SLV3), after which the ASC steers the operating point back to SLV3.

Note: Sudden opening or closing of the blow off valve either initiated by the Anti-surge controller or through manual control should not be done with caution for blowers with high power consumptions (such as the blower of 16.0078). The maximum speed at which the valve opens and closes must be controlled for such set-ups.

5 Description of anti-surge control strategy

Based on the above description, the anti-surge control loop will include two control strategies:

- PI-control generates an output aimed at steering R to a value which is equal to or greater than SLV3.
- Open loop control generates the output 'Preset1' for opening of the blow off valve to the inherent safe position (Preset1), in case the PI-control response is too slow.

Figure 3 displays the value of R along the secondary axis, indicating that R is approximately an exponential function of the suction volume flow. This means that the difference between SLV3 (a constant value) and R is not the most ideal input parameter for the PI-controller. It would produce a response which is much larger on the right side of SLV3 (if SLV3-R<0) than at equal distance on the left side of SLV3 (if SLV3-R>0). It is contrary to what is believed most beneficial, since the latter circumstance (SLV-R>0) is more critical, requiring the strongest response.
It has therefore been decided not to use R as input parameter for PI-control, but to use an inverse relationship: $(A/R)^n$. The constant A is just for the purpose of scaling so that the proportional and integral constants for PI-control are not too large or too small. An acceptable value of A is 1000. The exponent n is a user defined input variable which typically ranges from 0.2 to 1. See Figure 4. For n=0.2, the response is almost linear with the deviation in volume flow, whereas for n=1, the response progressively increases in the direction of lower flow rates.

The control strategy can be summarised as follows:

$$DEV = \left(\frac{1000}{R}\right)^n - \left(\frac{1000}{SLV3}\right)^n \qquad [4]$$

DEV>0 means that R<SLV3 → (further) open bypass valve by PI-control until DEV=0.
DEV<0 means that R>SLV3 → (further) close bypass valve by PI-control until DEV=0 or until valve is closed.

SLV2-R>0 → open bypass valve to Preset1 at predefined speed.

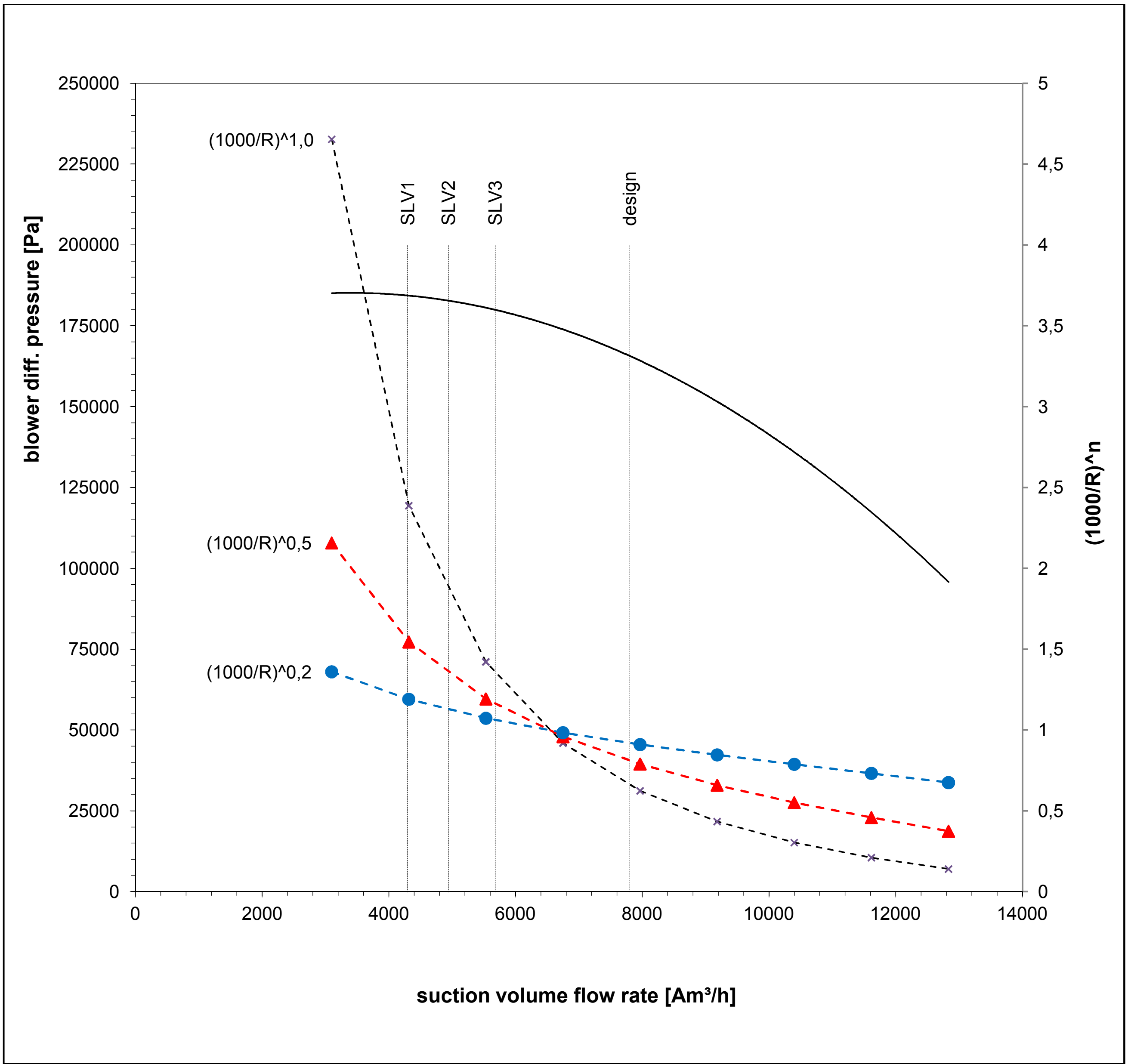

Figure 4: Blower performance curve (in black) and curves for control parameter $(1000/R)^n$ with n=0.2, n=0.5 and n=1 as function suction volume flow (along secondary axis). Values of Margin1 and Margin2 are 15%.

6 PLC Functional description

6.1 Process set points adjustable by authorised personnel

	Tag	Description	Default value	Unit
1	SLV1	surge limit value	417	m^4
2	margin1	defines SLV2=SLV1*(1+margin1)	15	%
3	margin2	defines SLV3=SLV2*(1+margin2)	15	%
4	M	molar mass	0,02737	kg/mole
5	preset1	ASC output for 'safety open mode'	100	% or mA
6	preset2	ASC output valve in closed position	0	% or mA
7	mode qv	select qvin or qvout (position of flow meter)	qvout	-
8	Kp	p-control constant		-
9	Ki	i-control constant		-
10	pin_max	maximum value of pin		bar
11	pout_max	maximum value of pout		bar
12	Δp_min	minimum value of Δp		bar
13	Tin_max	maximum value of Tin		°C
14	Tout_max	maximum value of Tout		°C
15	qvin_min	minimum value of qvin	4294	m^3/h
16	A	constant for PI-control parameter	1000	-
17	n	exponent for PI-control parameter	1	-
18	speed_max	maximum speed for opening and closing of valve		mA/s

6.2 Field inputs

	Tag	Description	Signal	Value	Range	Unit
1	10-PIT-5557	Inlet pressure	4-20 mA	0-100%	0-10	bar
2	10-TIT-8659	Inlet temperature	4-20 mA	0-100%	0-200	°C
3	10-PIT-5555	Outlet pressure	4-20 mA	0-100%	0-10	bar
4	10-TIT-5567	Outlet temperature	4-20 mA	0-100%	0-200	°C
5	10-FIT-5542	Volume Flow	4-20 mA	0-100%	0-8400	m3/h
6	S1	Switch on/off				-
7		Reset				

To filter out spikes the average is calculated of the last X samples.

6.3 Main parameters calculated from field inputs and process set points

	Tag	Description	Unit
1	SLV2	SLV2=SLV1*(1+margin1)	m^4
2	SLV3	SLV3=SLV2*(1+margin2)	m^4
3	qvin	qvout*pout*(Tin+273.14)/pin/(Tout+273.14)	m^3/h
4	R	$R = qvin^2 * M * pin / 8.31 / (Tin+273.14) / \Delta p$	m^4
5	DEV	$DEV = (A/R)^n - (A/SLV3)^n$	[-]

6.4 Field outputs

	Tag	Description	Signal	Value
1	10-FY-5542	Bypass valve position	4-20 mA	0-100%

See also paragraph 6.7.
It should be possible to change the output for bypass valves which 'fail open' to valve which 'fail closed'.

6.5 Locally displayed parameters

	Tag	Description	Unit
1	10-PIT-5557	Inlet pressure	bar
2	10-TIT-8659	Inlet temperature	°C
3	10-PIT-5555	Outlet pressure	bar
4	10-TIT-5567	Outlet temperature	°C
5	10-FIT-5542	Volume Flow	m3/h
6	R/SLV3	Deviation from control point (SLV3) x100%	%
7	10-FV-5542	Output signal to valve	mA

In addition to the abovementioned parameters, it is helpful to visualize R as function of time. The horizontal axis of the graph should display real time values with a maximum of 300 seconds.
The graph serves to determine the oscillating frequency, which helps to determine optimal values for the PI-control constants.

6.6 Displayed Alarms

	Tag	Description	Condition
1	10-TIT-8659	Inlet temperature too high	Tin > Tin_max
2	10-TIT-5567	Outlet temperature too high	Tout > Tout_max
3	10-PIT-5557	Inlet pressure too high	pin > pin_max
4	10-PIT-5555	Outlet pressure too high	pout > pout_max
5	10-PIT-5542	Flow too low	qvin < qvin_min
6		Pressure differential too low	$\Delta p<\Delta pmin$
7		Surge limit crossed	R<SLV1

The displayed alarms will be reset automatically. Displayed alarms are logged in a database. They can be cleared by authorized personnel only.

6.7 Communication between ASC and DCS

The input from the DCS to the ASC serves just to call for a data string with parameters from the ASC.
Upon the call for data string, all parameters mentioned in paragraphs 6.2, 6.4, 6.5, 6.6 are to be communicated by the ASC to the DCS.

6.8 Variables adjustable from ASC

Paragraph	Description	Tag	Signal	Value	Range	Unit
6.1	Process set points*			X		
6.2	Field inputs	X	X	X	X	
6.3	Calculated main parameters					
6.4	Field outputs	X	X	X		
6.5	Locally displayed parameters	X				
6.6	Displayed alarms	X				-
6.7	Parameters from and to DCS	IP addresses for communication				

* Process set points (paragraph 6.1) accessible by authorized personnel.
All other adjustable variables accessible by VTK, password: 'VTK1948RC'.

7 Display

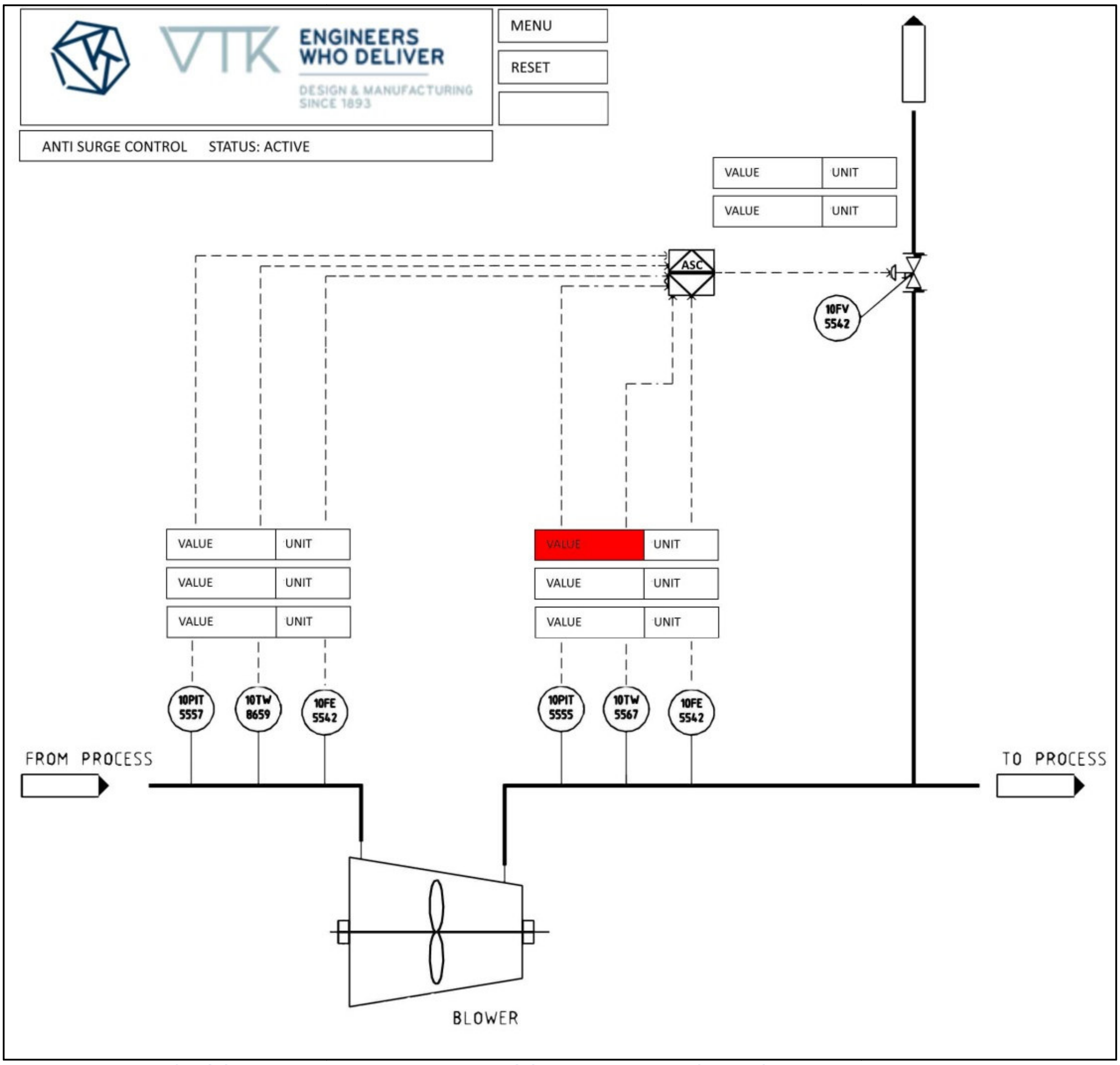

Figure 5: Example of ASC display with VTK logo, ASC status, simplified P&ID and locally displayed parameters. The menu button gives access to manually adjustable variables (paragraph 6.8). Alarms are displayed by a red background color of the applicable process parameter. Other buttons serve additional functions such as on/off, reset and light.

8 Algorithm (Note: just for the sake of explaining the basic functions)

Read user defined variables (set points only by authorized personnel)

SLV1

margin 1, margin 2

M

minimum and maximum values for qvin, Δpout, pin, Tin, 'input from DCS'

K_a, K_b

preset1

n, A, speed_max

qvin or qvout

Calculate:

SLV2 = SLV1 * (1 + margin1)

SLV3 = SVL1 * (1 + margin1) * (1 + margin2)

```
        Main loop
        Read pin
        Read pout
        Read Tin
        Read Tout
        Read qv
        Read input from DCS
        Δp = pout - pin

    IF  'qvout' THEN
        qvin = qvout*pout*Tin/(pin*Tpout)
END IF
        ρin*qvin^2 = qvin^2*M*pin/8.31/Tin
        R = ρin*qvin^2 / Δp
    IF  qvin OR Δp OR pin OR Tin OR R 'out of range' THEN
        GO TO safety routine
END IF
        Routine PI anti-surge control
        DEV = (A/R)^n – (A/SLV3)^n
    IF  DEV>0 THEN output such to further open bypass valve through PI-control
    IF  DEV<0 THEN output such to further close bypass valve through PI-control
    IF  SLV2 - R > 0 THEN output to preset1 with speed which equals speed_max
END IF
        Write parameters to DCS
        GO TO Main loop

        Safety routine
    IF  Δp < Δp_min THEN
        Write 'Δp out of range. ASC inactive.' to display and DCS (alarm)
    IF  qvin out of range THEN
        Write 'Flow out of range. ASC inactive.' to display and DCS (alarm)
    IF  R out of range THEN
        Write 'Surge limit crossed. ASC inactive.' to display and DCS (alarm)
    IF  pin out of range OR pout out of range
        Write 'p out of range.' to display and DCS (alarm)
    IF  Tin out of range OR Tout out of range THEN
        Write 'T out of range' to display and DCS (alarm)
        output = preset1
END IF
        GO TO Main loop
```