Case Study: Effects of Reboiler and Overhead Condenser Behaviors during Overfilling of Debutanizer Column to PRV Sizing.

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Abstract— **Overfilling or flooding is a condition where vapor flow is higher in comparison with the liquid flow thus prevents liquid from flowing into the downcomer effectively. This condition couples with a failure at the downcomer side of debutanizer column further creates an overpressure scenario. Such failure occurs when the control valve is in fail closed position causing a blocked liquid outlet. The degree of fatality caused by these failures and inability to properly address an overfilling event will affect the plant performance, create casualty and in worst case scenario significant loss of life. Therefore, this work studies the effect of overfilling at thermosyphon reboiler and overhead condenser and its impact to PRV sizing, safety feature essentials for any distillation column. The columns' parameters namely phase flow, temperature and flowrate are analyzed using Aspen HYSYS simulation and also manual calculation under four different debutanizer column's case profiles. Results obtained confirm that sizing of the PRVs varied according to each profile and that the mass flux of the incoming feed into a column is significant contributor to accurately size the PRV.**

Keywords*— *Overfilling, Pressure Relief Valve (PRV) Sizing, HYSYS Simulation, Debutanizer Column Profile's, Simplified Approach, API Recommended Practice 520.

I. Introduction

Separation is a "big business" in chemical processing due to its ability to separate one or more chemical mixtures during the processing. One of the separation equipment which is widely used in chemical industries in order to separate liquid and vapor is the distillation column. Distillation is described as a process or technique to separate two or more chemical components into an overhead distillate and also bottom product. The bottom product is in liquid phase, while the overhead distillate products are either in liquid, vapor or both phases [1].

There are many ways in which problem can affect distillation column performance and operation, one of which is overfilling. Overfilling in column is a condition where vapor flow is higher than its liquid flow thus liquid does not flow through the downcomer [2]. Previous researchers stated that vapor, liquid and feed flow condition (blockage at downstream line) are main factors that lead to performance and efficiency degradation of distillation which could also cause overfilling [3] and further creates an overpressure condition. Thus, jeopardize the performance of process parameters in reboiler, condenser and its downstream processes.

During overpressure itself, pressure build up from excessive vapor will hold liquid at the bottom part of the column, in this work at debutanizer. It results in the increase of liquid level and liquid hold up until it reaches the top trays and eventually reduces the overall column's efficiency, creating what we called as an overfilling phenomenon.

In industries, one of the methods to rectify overpressure and overfilling problems in distillation column is by installing the Pressure Relief Valve (PRV) systems [5]. In order to implement the PRV system, author must follow API Recommended Practice 520 Seventh Edition, January 2000 Sizing, Selection and Installation of Pressure-Relieving Devices in Refineries, Part I – Sizing and Selection as a guideline. The purposes of this recommended practice are to protect unfired pressure vessel such as distillation column and related equipment from excess of pressure (overpressure) during its operation.

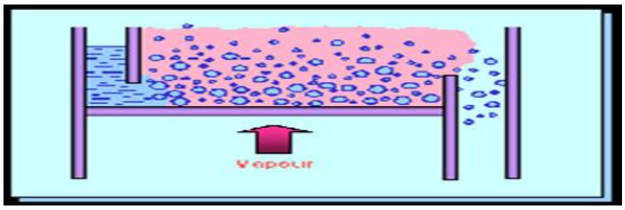

Figure 1: Illustration of Overfilling in Distillation Column [6]

In this study, author focuses more on overpressure of debutanizer column based on Debutanizer Column Case Profiles and PRV sizing. The overpressure scenario is established as follows:

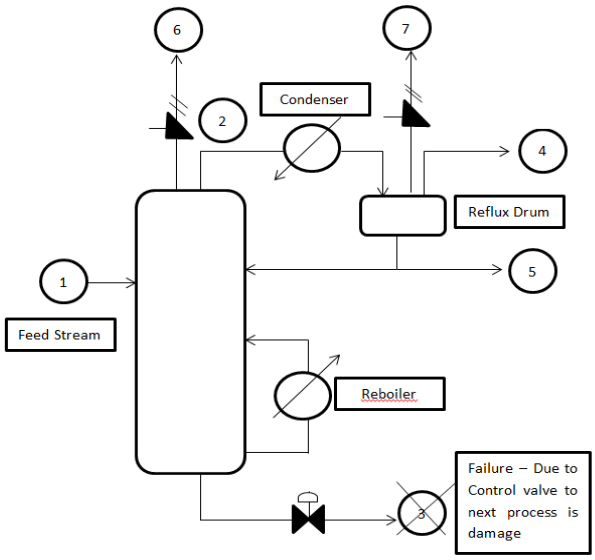

Figure 2: Schematic Diagram of Overpressure Event causes

First, the bottom stream system of debutanizer column is assessed to be in fail closed position. Refer to stream 3 in Figure 2. Due to this failure, fluids from feed stream 1 stops flowing into the bottom stream 3 resulting in the increment of liquid level hold up at the top trays. From here, the column's distillation process is no longer in its normal operating process efficiency and the overall mass balance has been interrupted.

There are 2 main methods used in this study, one is HYSYS simulation to determine the qualities and parameters of entering products at the PRVs based on four different case profiles by using Simplified Method Approach (SAF) and second are to determine the sizing/required area for each PRVs using manual calculations enlisted by API 520 [5].

A. Debutanizer Column's Profile

Event Case Scenario	
Condition	**Description**
Overfilling	Due to debutanizer column bottom stream failure, fluid stops flow to residue stream and hence increasing the level of liquid hold up on the plate above inside the column.
Overpressure	From the event scenario of overfilling the mass and parameters inside the column goes unbalance and then create overpressure condition.
Stream failure	This happened due to control valve located at the residue stream is damage (fail to open), and the damage of valve fail to detect by control system of debutanizer column.
Solution	
Solution	**Description**
Install Pressure Relief Valve (PRV)	-PRV is an alternative flow path to the Debutanizer column when flow in circuit is excess of pressure. It operates by opening at a designed pressure and ejecting mass from the process [8] -The removal mass contains energy, while the energy removal reduce the pressure process.

Table 1: Overfilling Case and its Solution

a) Debutanizer column's profile 1; during normal condition (reboiler and condenser continue to run and operate according to the column set up parameters), feed stream is 100% liquid phase and PRV is located at the top of debutanizer column.

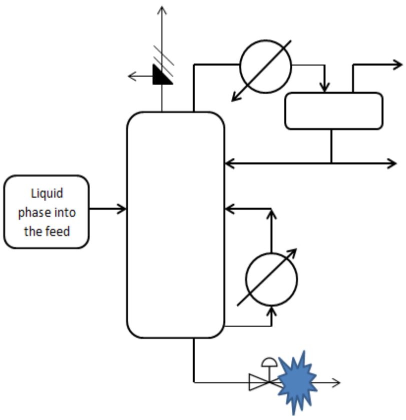

Figure 3: Debutanizer column's profile 1

b) Debutanizer column's profile 1; during normal condition (reboiler and condenser continue to run and operate according to the column set up parameters), feed stream is 100% liquid phase and PRV is located at the top of debutanizer column.

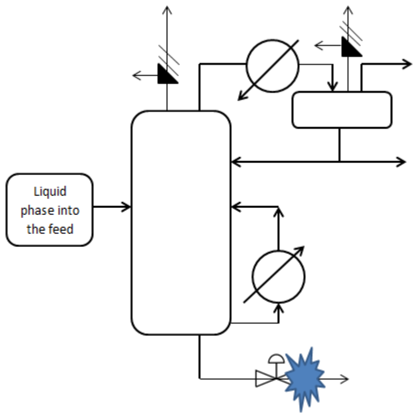

Figure 4: Debutanizer column's profile 2

c) Debutanizer column's profile 3; during normal condition (reboiler and condenser continue to run and operate according to the column set up parameters), feed stream is two phases (liquid and vapor) and PRV is located at the top of debutanizer column.

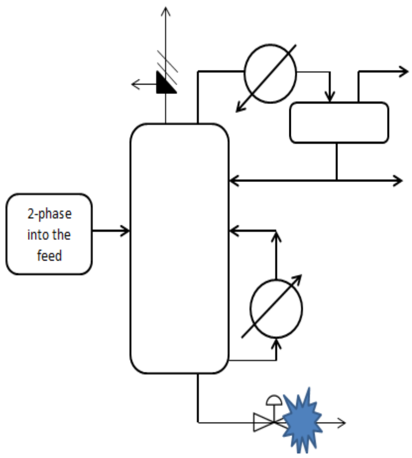

Figure 5: Debutanizer column's profile 3

d) Debutanizer column's profile 4; during normal condition (reboiler and condenser continue to run and operate according to the column set up parameters), feed stream is two phases (liquid and vapor) and feed stream is 100% liquid phase and PRV is located at the top of debutanizer column and reflux drum.

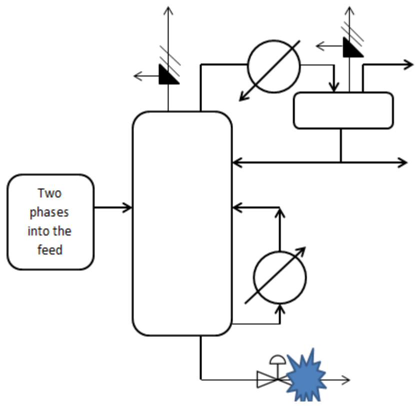

Figure 6: Debutanizer column's profile 4

During overpressure, the fluid phase of each stream and column's pressure constantly change. The fluid phase for each stream according to debutanizer columns' case profiles condition is shown in Table 2. This will be used to analyze each debutanizer column profile's stream fluid in order to perform PRV sizing. Stream and design of this fluid analysis based on Figure 2.

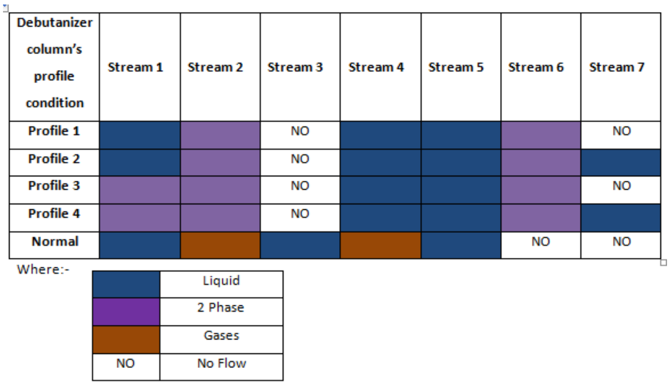

Figure 7: Phase of Fluid for Each Debutanizer Column

Based on the fluid analysis, during normal operation there are no fluid flow at PRV 1 and PRV 2 which is stream 6 and 7. During the abnormal condition which is during overfilling the phase for PRV 1 at each profile is two phase, while for PRV 2 is liquid phase for both debutanizer column profile's 2 and 4.

B. *Debutanizer (DeC4) & Deethanizer (DeC2) Design*

Debutanizer column (de-butaniser) is part of the fractional distillation family. The target fraction unit for debutanizer column is to fractionation and produce butane products Butane is a compound with chemical formula is C_4H_{10}.

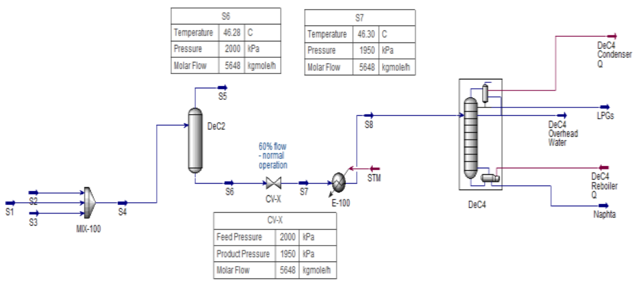

Figure 8: Simulation Process between Deethanizer and Debutanizer Column [7]

Figure 8 shows typical design of debutanizer column in fractionation section of LPG Manufacturing process. Commonly process of debutanizer same as the process of distillation, where distillation is one of the process uses to disparate mixtures according to its differences volatility of components in mixtures. The separation between mixtures happen interior of debutanizer column, and thus producing two types of products, which is top and bottom products. Regularly top product been produce, is a main product of the separation process which is in gases phase (butane gasses), while the bottom product will undergo another separation to obtained another desired product in liquid phase [9].

C. *Objective*

The main objective of this work is to study the effect of overfilling at thermosyphon reboiler and overhead condenser and its impact to PRV sizing under these following debutanizer column profile's:

1. Debutanizer column's profile 1; during normal condition (reboiler and condenser continue to run and operate according to the column set up parameters), feed stream is 100% liquid phase and PRV is located at the top of debutanizer column.
2. Debutanizer column's profile 2; during normal condition (reboiler and condenser continue to run and operate according to the column set up parameters), feed stream is 100% liquid phase and PRV is located at the top of debutanizer column and reflux drum.
3. Debutanizer column's profile 3; during normal condition (reboiler and condenser continue to run and operate according to the column set up parameters), feed stream is two phases (liquid and vapor) and PRV is located at the top of debutanizer column.
4. Debutanizer column's profile 4; during normal condition (reboiler and condenser continue to run and operate according to the column set up parameters), feed stream is two phases (liquid and vapor) and feed stream is 100% liquid phase and PRV is located at the top of debutanizer column and reflux drum.

II. METHODOLOGY

A. *Software*

The software used throughout this case study is Aspen HYSYS simulation and Microsoft Excel. Aspen HYSYS simulation is used to simulate the Debutanizer columnn's case profiles conditions and gathering the input parameters for PRV sizing. Process parameters such as temperature, pressure, flow rate and composition studied in this simulation were obtained from the industry. Peng-Robinson fluid package is used to carry out all the experimental simulations for its flexibility and suitability in hydrocarbon system [8]. Microsoft Excel is used to determine the PRV sizing which is required by inserting the equation of PRV sizing manually.

B. *Method*

API Recommended Practice 520 Seventh Edition, January 2000 Sizing, Selection and Installation of Pressure-Relieving Devices in Refineries, Part I – Sizing and Selection, this recommended practice applies to sizing and selection of pressure relief valve (PRV) used in refineries and any related industries for equipment with MAWP of 15 psig (103 kPag) or greater. The purpose of this recommended practice is to protect unfired pressure vessel such as distillation column and related equipment from excess of pressure during its operation. However, it does not protect vessel against structural failure such as exposure to extremely high temperature due to fire.

a) Sizing for Two-Phase Flashing or Non-flashing Flow Through a Pressure Relief Valve

The method presented in this section can be used for sizing PRV that handles either flashing or non-flashing flow. For flashing, the two-phase system must consist of a saturated liquid and saturated vapor and contain no non-condensable gases. While for non-flashing flow, the two-phase system must consist of highly subcooled liquid and either a non-condensable gas, condensable vapor or both

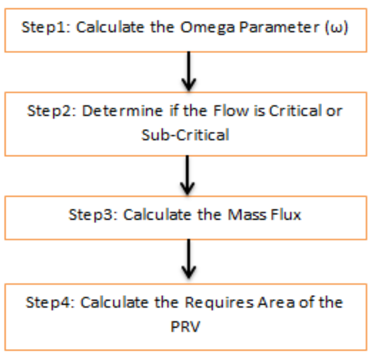

Figure 9: Step to Calculate Sizing of Two-Phase Flow [5]

Step 1: Calculate the Omega Parameter (ω)

For flashing multi-component system with nominal boiling point range less than 150^{0}F or flashing single component system use Equation 1.

$$\omega = \frac{x_o\, v_{vo}}{v_o\, k} + \frac{0.185\, C_p\, T_o\, P_o}{v_o}\left(\frac{v_{vlo}}{h_{vlo}}\right)^2 \qquad \text{Eq-1}$$

Where:

X_0 = vapor mass fraction (quality) at the PRV inlet

V_{v0} = specific volume of the vapor at the PRV inlet (ft3/lb)

V_0 = specific volume of the two-phase system at the PRV inlet (ft3/lb)

P_0 = Pressure at the PRV inlet (psia). This is the PRV set pressure (psig) plus the allowable overpressure (psia) plus atmospheric pressure.

V_{vl0} = different between the vapor and liquid specific volumes at the PRV inlet (ft3/lb)

h_{vl0} = Latent heat of vaporization at the PRV inlet (Btu/lb). For multi component system

Cp = Liquid specific heat at constant pressure at the PRV inlet (Btu/lb.R)

T_0 = Temperature at the PRV inlet (R)

k = Ratio of the specific heat of the vapor. If the specific heat ratio is unknown, a value 1.0 is used

Step 2: Determine if the Flow is Critical or Subcritical

Pc > Pa ------> Critical flow
Pc < Pa ------> Subcritical flow

Where:

Pa = downstream back pressure (psia)

Pa = (Superimposed back pressure) + (build up back pressure)

Pc = Critical pressure (psia)

Pc = ηc Po

Po = Pressure at the PRV inlet (psia). This is the PRV set pressure (psig) plus the allowable overpressure (psia) plus atmospheric pressure

η_c = critical pressure ratio, use Figure 10.

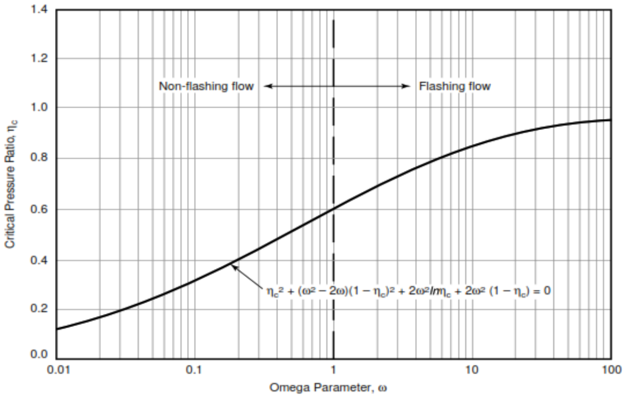

Figure 10: Correlation for Nozzle Critical Flow of Flashing or Nonflashing Systems [5]

Step 3: Calculate the Mass Flux

For critical flow use Equation 2, while for subcritical flow use Equation 3.

$$G = 6.809\ \eta c \sqrt{\frac{P_o}{v_o \omega}} \qquad \text{Eq-2}$$

$$G = \frac{68.09\left\{-2\left[\frac{\omega}{n\eta a} + (\omega - 1)(1 - \eta a)\right]\right\}^{1/2}}{\omega\left(\frac{1}{\eta a} - 1\right) + 1}\sqrt{\frac{P_0}{v_0}} \qquad \text{Eq-3}$$

Where:

G = mass flux (lb/s.ft2)

ηa = back pressure ratio

ηa = Pa/Po

Step 4: Calculate the Area of the PRV

Area of PRV calculates by using Equation 4.

$$A = \frac{0.04\, W}{K_d K_b K_c G} \qquad \text{Eq-4}$$

Where:

A = required effective discharge area (in2)

W = mass flow rate (lb/hr)

Kd = Discharge coefficient that should be obtained from the valve manufacturer. For a preliminary sizing estimation, a discharge coefficient of 0.85 can be used.

Kc = Combination correction factor for installation with a rupture disk upstream of the PRV.

(1.0 when rupture disk not install, while 0.9 when rupture disk installed in combination with a PRV and the combination does not have a published value.)

Kb = Back pressure correction factor for vapor that should be obtained from the valve manufacturer. The back pressure correction factor only applied to balanced-bellow valve only. Use Figure 11. For balance PRV, superimposed back pressure will not affect the set pressure of the relief valve. Kb for this case could either be set equal to 1.0 or can be based on an assumed total back pressure

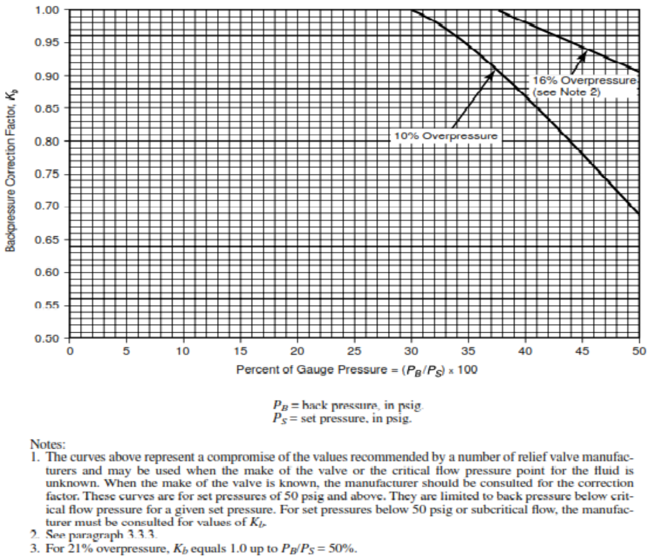

Figure 11: Back Pressure Correction Factor, Kb [5]

b) Sizing For Subcooled Liquid at the PRV Inlet.

The method was used to calculate sizing for PRV handling a subcooled (including saturated) liquid at the inlet. The inlet flow system PRV must be liquid with no condensable vapor or non-condensable gas should be present. The method of calculation, also apply to all liquid scenario.

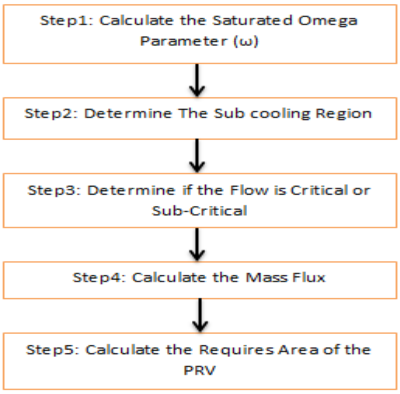

Figure 12: Step to Calculate Sizing of Liquid Flow through a PRV [5].

Step 1: Calculate the Omega Parameter, ω

Applied to multi-components system with boiling range less than 150^{O}F or to single component system, use either Equation 5 or 6. For Equation 5, the fluid must be far from its thermodynamic critical point.

$$\omega_s = 0.185\ \rho_{lo}\, T_o\, P_s \left(\frac{v_{vls}}{h_{vls}}\right)^2 \qquad \text{Eq-5}$$

$$\omega_s = 9\left(\frac{\rho_{lo}}{\rho_9} - 1\right) \qquad \text{Eq-6}$$

Where;-

ρ_{lo} = Liquid desnsity at the PRV inlet (ft3/lb)

C_p = Liquid specific heat at constant pressure (Btu/lb.R)

T_0 = Temperature at the PRV inlet (R)

Ps = Saturation (vapor) pressure corresponding to T0 (psia)

v_{vl0} = different between the vapor and liquid specific volumes at the PRV inlet (ft3/lb)

h_{vls} = Latent heat of vaporization at Ps (Btu/lb). For multi component system, hvls is the different between the vapor and liquid specific enthalpies

v_{vls} = Different between the vapor and liquid specific volume at Ps (ft3/lb)

P_9 = Density evaluate at 90% of the saturation (vapor) pressure Ps (lb /ft3)

Step 2: Determine the Sub-cooling Region

If there:

Ps > ηst Po ---> Low sub-cooling region
Pc < ηst Po---> High Sub-cooling region

Where;-

ηst = Transition saturation pressure ratio
$= \frac{2\omega_s}{1+2\omega_s}$

P_0 = Pressure at the PRV inlet (psia). This is the PRV set pressure (psig) plus the allowable overpressure (psia) plus atmospheric pressure.

Step 3: Determine if the Flow is Critical or Subcritical

c) For low sub-cooling region

Pc > Pa ------> Critical flow
Pc < Pa ------> Subcritical flow

d) For high sub-cooling region

Ps > Pa ------> Critical flow
Ps < Pa ------> Subcritical flow (all liquid)

Where;-

P_a = downstream back pressure (psia)
= (Superimposed back pressure) + (build up back pressure)

Ƞs = Saturation pressure ratio (Ps/Po)

P_c = Critical pressure (psia)

Pc = ηc Po

ηc = critical pressure ratio (use Figure 13)

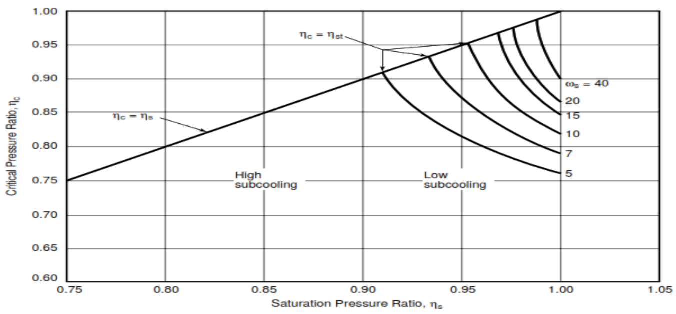

Figure 13: Correlation for Nozzle Critical Flow of Inlet Subcooled Liquids [5]

Step 4: Calculate the Mass Flux

If there was low sub-cooling region, use the Equation 3.10. In Equation 7, if the flow was critical change η to ηc, while if the flow was subcritical change η to ηa.

Eq-7:

$$G = \frac{68.09\left\{2(1-\eta s)\left[\omega s\, \eta s\, ln\left(\frac{\eta s}{\eta}\right) - (\omega s - 1)(\eta s - \eta)\right]\right\}^{1/2}}{\omega s\left(\frac{\eta s}{\eta} - 1\right) + 1}\sqrt{Po\, \rho_{lo}}$$

For high sub-cooling region, use Equation 8. In the Equation 8, if the flow was critical flow, use change P to Ps, while if the flow was subcritical flow change P to Pa.

Eq-8:

$$G = 96.3\left[\rho_{lo}(Po - p)\right]^{1/2}$$

Where;-

G = Mass flux (lb/s.ft^2)

ηa = back pressure ratio (Pa/Po)

Step 5: **Calculate the Required Area of the PRV**

The Equation 9 is only applicable for turbulent system flow only. Commonly, most of two phase relief scenario is turbulent flow system.

Eq-9:

$$A = 0.3208\frac{Q\rho_{lo}}{K_d K_b K_c G}$$

Where;-

A = required effective discharge are (In^2)

Q = Volumetric flow rate (gal/min)

III. RESULTS AND DISCUSSION

In The results are divided into two sections, A and B. The first section, which is section A discussed on Simplified Approach Method in order to determine the phase of PRVs (PRV 1 and PRV 2) whether it is liquid phase or two-phase, and hence to determine the relief quality of PRV. Section B discussed on PRVs sizing for each Debutanizer column's case profile (1, 2, 3 and 4) based on API 520 [5]

A. Simplified Approach Method

1. Feed Stream

From Figure 8, the feed stream of Deethanizer column (S4) is used in the simplified approach simulation as feed stream condition. The phase and temperature of stream 4 (S4) has been changed according to Debutanizer column's profile to allow for simple HYSYS simulation. In simplified approach method, stream S-4 is being named as S4-2, refer Figure 18 with initial two-phase component feed and its process parameters such as temperature at 46.28^{0}C and pressure at 2000.00 kPa.

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*For feed stream (S4-2) applied for Debutanizer column's profile 3 and 4.

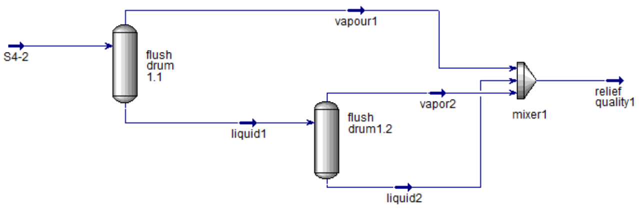

Figure 14: Simplified Approach for Two-Phase Feed Stream

*Figure 14 with S4-2 feed stream is applicable for Debutanizer column's case profile 3 and 4.

Worksheet	Stream Name	S4-2
Conditions	Vapour / Phase Fraction	0.0013
Properties	Temperature [C]	46.28
Composition	Pressure [kPa]	2000
Oil & Gas Feed	Molar Flow [kgmole/h]	5656
Petroleum Assay	Mass Flow [kg/h]	5.125e+005
K Value	Std Ideal Liq Vol Flow [m3/h]	730.3
User Variables	Molar Enthalpy [kJ/kgmole]	-1.894e+005
Notes	Molar Entropy [kJ/kgmole-C]	169.5
Cost Parameters	Heat Flow [kJ/h]	-1.071e+009
Normalized Yields	Liq Vol Flow @Std Cond [m3/h]	721.7
	Fluid Package	Basis-1
	Utility Type	

Figure 15: Stream 4 (S4-2) Conditions with Vapor Phase Fraction 0.0013

Worksheet		Vapour Phase	Liquid Phase
Conditions	Hydrogen	0.8051	0.0118
Properties	Methane	0.0629	0.0054
Composition	Ethane	0.0394	0.0159
Oil & Gas Feed	Propane	0.0450	0.0572
Petroleum Assay	i-Butane	0.0099	0.0289
K Value	n-Butane	0.0146	0.0587
User Variables	i-Pentane	0.0048	0.0446
Notes	n-Pentane	0.0054	0.0647
Cost Parameters	n-Hexane	0.0016	0.0525
Normalized Yields			

Figure 16: Stream 4 (S4-2) Composition with Vapor Phase Fraction 0.0013

In order to change phase of stream 4 (S4) of Figure 8 from two phase to liquid phase, the temperature of stream 4 is being reduced from 46.28^{0}C to -240.0^{0}C, i.e. below the boiling point of components in feed stream, while the pressure and composition of component mole fraction remains. The new stream 4 is being named as S4-4, refer Figure 17.

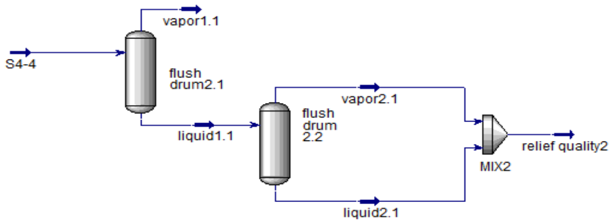

*Figure 17 with S4-4 feed stream is applicable for Debutanizer column's case profile 1 and 2.

Worksheet	Stream Name	S4-4
Conditions	Vapour / Phase Fraction	0.0000
Properties	Temperature [C]	-240.4
Composition	Pressure [kPa]	2000
Oil & Gas Feed	Molar Flow [kgmole/h]	5656
Petroleum Assay	Mass Flow [kg/h]	5.125e+005
K Value	Std Ideal Liq Vol Flow [m3/h]	730.3
User Variables	Molar Enthalpy [kJ/kgmole]	-2.290e+005
Notes	Molar Entropy [kJ/kgmole-C]	-108.9
Cost Parameters	Heat Flow [kJ/h]	-1.295e+009
Normalized Yields	Liq Vol Flow @Std Cond [m3/h]	721.7
	Fluid Package	Basis-1
	Utility Type	

Figure 18: Stream 4 (S4-4) Condition with Vapor Phase Fraction 0.00

Worksheet		Liquid Phase	Aqueous Phase	Vapour Phase
Conditions	Hydrogen	0.0129	0.0000	1.0000
Properties	Methane	0.0054	0.0000	0.0000
Composition	Ethane	0.0159	0.0000	0.0000
Oil & Gas Feed	Propane	0.0572	0.0000	0.0000
Petroleum Assay	i-Butane	0.0289	0.0000	0.0000
K Value	n-Butane	0.0587	0.0000	0.0000
User Variables	i-Pentane	0.0446	0.0000	0.0000
Notes	n-Pentane	0.0646	0.0000	0.0000
Cost Parameters	n-Hexane	0.0525	0.0000	0.0000
Normalized Yields				

Figure 19: Stream 4 (S4-4) Composition with Vapor Phase Fraction 0.00

2. Design

Basic design for Simplified Approach Method includes two flush drum and one mixer. The 1st flush drum incoming feed stream consists of either liquid or two-phase components, while the incoming for 2nd flush drum is from the bottom outlet stream of the 1st flush drum. The top stream of 1st flush drum (if been feeding by two-phase of component), top stream and bottom stream of 2nd flush drum been connected to the mixer. This is to mimic the condenser unit arrangement at the top of a debutanizer column in order to be able to simulate the condenser behavior.

Based on the design approach the relief quality of PRV 1 is obtained from the mixer outlet while the relief quality of PRV2 is gained from the bottom outlet of 2nd flush drum. PRV 1 represents the relief valve located at the reflux drum while PRV 2 represents relief valve located at the top of debutanizer column. Refer Figure 2.

In the case of overfilling contingency, it is assumed that the liquid accumulation is causing an entrainment to the distillated drum via overhead condenser. Continuous liquid feed causes the liquid level in the distillate drum to rise and eventually causes overpressure. The relief quality through PRV 2 is expected to be 100% liquid phase, while for the relief quality through PRV 1 is of two-phase components.

3. Result

This section shows the result for each debutanizer column profile's (profile 1, profile 2, profile 3 and profile 4) after Simplified Approach Method been done. The results discuss on phases of Pressure Relief Valve (PRV) inlet and vapor phase fraction values at each Pressure Relief Valve inlet streams.

Debutanizer column's profile 1

Condition	-Liquid phase flow fed into feed stream -Bottom system of column failure. There is no flow at the bottom stream. -1 PRV - pressure relief valve located at top of column
Phase	-Two-phase component at Pressure Relief Valve 1(PRV1)
Vapor/Phase fraction	-At relief quality 2 stream: - shown the value of vapor/phase fraction for pressure relief valve (PRV 1) is 0.0129, where it is two phase component.

Table 2: Debutanizer column's profile 1

Debutanizer column's profile 2

Condition	-Liquid phase flow fed into feed stream -Bottom system of column failure. There is no flow at the bottom stream. -2 PRV - pressure relief valve located at top of column and top of reflux drum
Phase	-Two-phase component at Pressure Relief Valve 1(PRV1) -Liquid phase component at Pressure Relief Valve 2 (PRV2)
Vapor/Phase fraction	-At relief quality 2 stream: - shown the value of vapor/phase fraction for pressure relief valve (PRV 1) is 0.0129, where it is two phase component. -At liquid 2.1 stream: - shown the value of vapor/phase fraction for pressure relief valve (PRV 2) is 0.0000, where it is liquid phase component.

Table 3: Debutanizer column's profile 2

Figure 20 and Figure 21 show the components' condition for streams of relief quality 2 and liquid 2.1. Both of Debutanizer column's profile 1 and 2 use same design (Figure 17) of simplified approach method with same condition and composition of feed stream (S4-4), which is liquid phase feed component. From the design approach, the stream relief quality 2 is used to determine value of relief quality for PRV 1; Debutanizer column's case profile 1 and 2, while stream liquid 2.1 to determine relief quality for PRV 2; Debutanizer column's case profile 2.

Worksheet	Stream Name	relief quality2	Vapour Phase	Liquid Phase	Aqueous Phase
Conditions	Vapour / Phase Fraction	0.0129	0.0129	0.9866	0.0005
Properties	Temperature [C]	-239.9	-239.9	-239.9	-239.9
Composition	Pressure [kPa]	2000	2000	2000	2000
Oil & Gas Feed	Molar Flow [kgmole/h]	5656	72.98	5580	2.562
Petroleum Assay	Mass Flow [kg/h]	5.125e+005	147.1	5.123e+005	46.15
K Value	Std Ideal Liq Vol Flow [m3/h]	730.3	2.106	728.2	4.624e-002
User Variables	Molar Enthalpy [kJ/kgmole]	-2.290e+005	-8292	-2.319e+005	-3.099e+005
Notes	Molar Entropy [kJ/kgmole-C]	-107.8	18.03	-109.4	-163.7
Cost Parameters	Heat Flow [kJ/h]	-1.295e+009	-6.051e+005	-1.294e+009	-7.939e+005
Normalized Yields	Liq Vol Flow @Std Cond [m3/h]	721.7	1726	718.4	4.548e-002

Figure 20: Condition of Stream Relief Quality 2 Condition

Worksheet	Stream Name	liquid2.1	Liquid Phase	Aqueous Phase	Vapour Phase
Conditions	Vapour / Phase Fraction	0.0000	0.9995	0.0005	0.0000
Properties	Temperature [C]	-240.4	-240.4	-240.4	-240.4
Composition	Pressure [kPa]	2000	2000	2000	2000
Oil & Gas Feed	Molar Flow [kgmole/h]	5656	5653	2.562	0.0000
Petroleum Assay	Mass Flow [kg/h]	5.125e+005	5.124e+005	46.15	0.0000
K Value	Std Ideal Liq Vol Flow [m3/h]	730.3	730.3	4.624e-002	0.0000
User Variables	Molar Enthalpy [kJ/kgmole]	-2.290e+005	-2.290e+005	-3.100e+005	-8319
Notes	Molar Entropy [kJ/kgmole-C]	-108.9	-108.9	-165.6	17.16
Cost Parameters	Heat Flow [kJ/h]	-1.295e+009	-1.294e+009	-7.941e+005	0.0000
Normalized Yields	Liq Vol Flow @Std Cond [m3/h]	721.7	721.6	4.548e-002	0.0000

Figure 21: Condition of Stream 2.1 Liquid Condition

Debutanizer column's profile 3

Condition	-Two phase flow fed into feed stream -Bottom system of column failure. There is no flow at the bottom stream. -1 PRV - pressure relief valve located at top of column
Phase	-Two-phase component at Pressure Relief Valve 1(PRV1)
Vapor/Phase fraction	-At relief quality 1 stream: - shown the value of vapor/phase fraction for pressure relief valve (PRV 1) is 0.0013, where it is two phase component.

Table 4: Debutanizer column's profile 3

Debutanizer column's profile 4

Condition	-Two phase flow fed into feed stream -Bottom system of column failure. There is no flow at the bottom stream. -2 PRV - pressure relief valve located at top of column and top of reflux drum
Phase	-Two-phase component at Pressure Relief Valve 1(PRV1) -Liquid phase component at Pressure Relief Valve 2 (PRV2)
Vapor/Phase fraction	-At relief quality 1 stream: - shown the value of vapor/phase fraction for pressure relief valve (PRV 1) is 0.0013, where it is two phase component. -At liquid 2 stream: - shown the value of vapor/phase fraction for pressure relief valve (PRV 2) is 0.0000, where it is liquid phase component.

Table 5: Debutanizer column's profile 4

Figure 22 and Figure 23 shown the component's condition for streams of relief quality 1 and liquid 2. Both of Debutanizer column's profile 3 and 4 use same design (Figure 14) of simplified approach method with same condition and composition of feed stream (S4-2), which is two phase feed component. From the design approach, the stream relief quality 1 used to determine value of relief quality for PRV 1; Debutanizer column's case profile 3 and 4, while stream liquid 2 to determine relief quality for PRV 2; Debutanizer column's case profile 4.

Worksheet	Stream Name	relief quality1	Vapour Phase	Liquid Phase
Conditions	Vapour / Phase Fraction	0.0013	0.0013	0.9987
Properties	Temperature [C]	46.28	46.28	46.28
Composition	Pressure [kPa]	2000	2000	2000
Oil & Gas Feed	Molar Flow [kgmole/h]	5656	7.546	5648
Petroleum Assay	Mass Flow [kg/h]	5.125e+005	67.29	5.124e+005
K Value	Std Ideal Liq Vol Flow [m3/h]	730.3	0.2935	730.0
User Variables	Molar Enthalpy [kJ/kgmole]	-1.894e+005	-1.882e+004	-1.897e+005
Notes	Molar Entropy [kJ/kgmole-C]	169.5	118.0	169.5
Cost Parameters	Heat Flow [kJ/h]	-1.071e+009	-1.420e+005	-1.071e+009
Normalized Yields	Liq Vol Flow @Std Cond [m3/h]	721.7	178.4	721.3

Figure 22: Condition of Stream Relief Quality 1 Condition

Worksheet	Stream Name	liquid2	Vapour Phase	Liquid Phase
Conditions	Vapour / Phase Fraction	0.0000	0.0000	1.0000
Properties	Temperature [C]	46.28	46.28	46.28
Composition	Pressure [kPa]	2000	2000	2000
Oil & Gas Feed	Molar Flow [kgmole/h]	5648	0.0000	5648
Petroleum Assay	Mass Flow [kg/h]	5.124e+005	0.0000	5.124e+005
K Value	Std Ideal Liq Vol Flow [m3/h]	730.0	0.0000	730.0
User Variables	Molar Enthalpy [kJ/kgmole]	-1.897e+005	-1.882e+004	-1.897e+005
Notes	Molar Entropy [kJ/kgmole-C]	169.5	118.0	169.5
Cost Parameters	Heat Flow [kJ/h]	-1.071e+009	0.0000	-1.071e+009
Normalized Yields	Liq Vol Flow @Std Cond [m3/h]	721.3	0.0000	721.3

Figure 23: Condition of Stream Liquid 2 Condition

B. *PRV sizing for each Debutanizer column's profile*

1. Result for PRV 1 and Discussion

Inlet of Pressure Relief Valve 1 (PRV 1) for each Debutanizer Columns' Profile is of two-phase components. Under this condition, results for each profile (profile 1, 2, 3 and 4) shown in Figure (24, 25 and 26) have been calculated using Sizing for Two-Phase Flashing or Non-flashing Flow through a Pressure Relief Valve methods.

Debutanizer Column Profile's										
Omega parameter										
Valve 1 - Two Phase										
	Xo	Vvo	Vo	Cp	To	Po	Vvlo	hvlo	k	ω
Profile 1	0.0002871	0.306	0.0189	0.284	59.85	333.7789	0.2867	1086.414	1	0.01
Profile 2	0.0002871	0.306	0.0189	0.284	59.85	351.1835	0.2867	1086.414	1	0.01
Profile 3	0.0001313	2.3803	0.0237	0.5138	574.974	333.7789	2.3463	898.9682	1	6.0353
Profile 4	0.0001313	2.3803	0.0237	0.5138	574.974	351.1835	2.3463	898.9682	1	5.5321

Figure 24: Result for Omega Parameter

Figure 24 shows the value of parameters required in order calculate Saturated Omega Parameter (ω) for PRVs under each debutanizer column profile's condition. The parameter of Ratio of the Specific Heat of the Vapor (k) is assumed to be at a constant value of 1.0. Values of Saturated Omega Parameter (ω) obtained for profile 1 and profile 2 are found to be the same, i.e. 0.01.

		Subcooling region & mass flux				
	ηc	Po(psia)	pc(psia)	Pa(psia)	flow	G (lbs/s.ft2)
Profile 1	0.12	333.7789	40.0535	14.5038	Critical	10858.332
Profile 2	0.12	351.1835	42.142	14.5038	Critical	11137.8337
Profile 3	0.8	333.7789	267.023	14.5038	Critical	2631.3533
Profile 4	0.78	351.1835	273.9231	14.5038	Critical	2748.903

Figure 25: Result for Subcooled Region and Mass Flux

Figure 25 shows the result for subcooled region for each profile whether it is under critical or sub-critical flow. The value of critical pressure ratio (ηc) is determined using Saturated Omega Parameter (ω) in Figure 10 . If the profile is in critical flow category, then Equation D.2 is used to find Mass Flux (G) and for subcritical flow Equation D.3 is being used. All the case profiles (profile 1, 2, 3 and 4) are calculated to be in critical flow condition, given that the value of critical pressure (Pc) is greater than the value of downstream back pressure (Pa).

		Required area			
	w (lb/hr)	Kd	Kb	Kc	A (in2)
Profile 1	1129869.09	0.85	1	1	4.8967
Profile 2	1129869.09	0.85	1	1	4.7738
Profile 3	1129869.09	0.85	1	1	20.21
Profile 4	1129869.09	0.85	1	1	19.3439

Figure 26: Result for Required PRV Sizing

Figure 26 shows the results of PRV1 sizing or area in inches squared (in2) required for each debutanizer column's case, where it gives the final area for pressure relief valve required. For parameters Discharge coefficient (Kd), Back pressure correction factor for vapor (Kb) and combination correction factor for installation (Kc) for each profile is constant at 0.85, 1.0 and 1.0. For this case it is assumed that the PRVs are not installed with rupture disk and therefore, a Balance Pressure Relief Valve type is being used.

2. Result for PRV 2 and Discussion

Pressure Relief Valve 2 (PRV 2) only applies to Debutanizer column's case profile 1 and 2. Based on Simplified Approach method analysis, both inlets of PRV 2 for Debutanizer column's case profile 1 and 2 was liquid phase condition. For liquid phase condition, the result shown for both profile (1 and 2) shown in Figure (27, 28, 29, 30 and 31). Both results are calculated based on method shown in methodology which is sizing for subcooled liquid at the pressure relief valve inlet.

Debutanizer Column Profile's							
Omega parameter							
Valve 2 - Liquid Phase							
	Ps (psia)	Cp (Btu/lb.R)	ρlo(lb/ft3)	To (R)	hvls (Btu/lb)	vvls (ft3/lb)	ωs
Profile 2	290.0755	0.2859	52.7766	123.75	1086.414	0.0189	0.00003
Profile 4	290.0755	0.5135	42.6446	574.974	898.5383	2.3386957	4.5773

Figure 27: Omega Parameter Value

Figure 27 shows the result of parameter required for each Debutanizer column's case profile 2 and 4 in order to calculate Saturated Omega Parameter (ωs). All the parameter value gathers from Aspen Hysys simulation which is simplified approach method. For profile 2, the parameter's values gather from Stream Liquid 2.1 is shown in Figure 21, while for profile 4 the parameter's value is gathered from Stream Liquid 2.0 shown in Figure 23. Based on the result, the value omega for Debutanizer column's case profile's 2 is smaller compared to Debutanizer column case profile's 4. The huge difference in Omega values for both profiles are caused by the difference between the vapor and liquid specific volume (Vvls) values.

Sub-cooling region					
Valve 2 - Liquid Phase					
	Po (psia)	ηst	ηst x Po	Ps (psia)	Sub-cooling region
Profile 2	334.3591	0.00006	0.02	290.0755	Low
Profile 4	334.3591	0.9015	301.4247	290.0755	High

Figure 28: The Sub-cooling Region

Figure 28 shows the results of sub-cooling region for each Debutanizer column case profile's 2 and 4, whether it is a low sub-cooling region or high sub-cooling region. During the calculation, values of transition saturation pressure ratio (ηst) for profile 2 are 0.0006 which smaller compare to saturation pressure ratio at profile 4. The huge differences value for both Debutanizer Column Profile's due to value of Saturated Omega Parameter (ωs). The region for Debutanizer column case profile's 2 is low sub-cooling region due to value of saturation pressure (Ps) is higher compare to value of ηst x Po, while region of Debutanizer column case profile's 4 is high sub-cooling region due to value of ηst x Po is higher compare to value of saturation pressure (Ps).

Flow (Critical or Sub-critical)							
Valve 2 - Liquid Phase							
	Ps(psia)	Pa (psia)	ηs	ηc	Po (psia)	Pc (psia)	flow
Profile 2	290.0755	14.5038	0.87	0.87	334.3591	290.8924	Critical
Profile 4	290.0755	14.5038	-	-	-	-	Critical

Figure 29: Flow of Debutanizer Column's Profile

Based on sub-cooling region ,the flow of Debutanizer columns' case profiles can be determine whether it is critical of subcritical flow based on step 3 in methodology which is Sizing For subcooled Liquid at the Pressure Relief Valve Inlet. For Debutanizer column's case profile 2 the flow is critical due to value of (critical pressure) Pc is greater than value of back pressure (Pa). For Debutanizer column's case profile 4 the flow also critical flow, due to value of saturation pressure (Ps) is greater than value of back pressure (Pa).

Mass Flux					
Valve 2 - Liquid Phase					
	Po (psia)	P (psia)	ρlo(lb/ft3)		G (lbs/s.ft2)
Profile 4	334.3591	P = Ps = 290.0755	42.6446		4184.8488
	ηs	η	ωs	ρlo(lb/ft3)	Po (psia)	G (lbs/s.ft2)
Profile 2	0.87	η = ηc = 0.87	0.00003	52.7766	334.3591	12791.6467

Figure 30: Value of Mass Flux

For Debutanizer column's case profile 4 the mass flux calculate by using Equation 7 because there was low sub-cooling region, while Debutanizer column's Profile 2 the mass flux calculate by using Equation 8 because of there was high sub-cooling region. During calculation of Debutanizer column's case profile 4, based on the rule if flow is critical flow the ratio (η) is changed to critical pressure ratio (ηc) critical which can be determined by using Figure 13. Correlation for Nozzle Critical Flow of Inlet Subcooled Liquids based on value saturation pressure ratio (ηs) at 0.87. During calculation of Debutanizer column's case profile 2, the flow also critical flow the value of pressure (P) is changed to saturation pressure (Ps). Based on the result, values of mass flux for Debutanizer column's case profile 4 is smaller compare to Debutanizer column's case profile 2.

Required area							
Valve 2 - Liquid Phase							
	Q (gal/min)	ρlo(lb/ft3)	Kc	Kd	Kb	G (lbs/s.ft2)	Area (in2)
Profile 2	2668.578	52.7766	1	0.65	1	12791.6467	5.434
Profile 4	3302.509	42.6446	1	0.65	1	4184.8488	12.7012

Figure 31: Result for Required PRV 2 Sizing

Figure 31 shows the final result for sizing for subcooled liquid at the pressure relief valve 2 Inlet in inches squared (in^2). Both of the pressure relief valve not installed with rupture disk the value of combination correction factor for installation (kc) is equal to 1.0. For this case Balance Pressure Relief Valve types are being used, so the correction factor (kb) be set initially equal to 1.0. While for the discharge coefficient (kd) value is set equal to 0.65 for subcooled liquids. From the calculation, the area or sizing required for Debutanizer column's case profile 4 is bigger compare to Debutanizer column's case profile 2 which is 12.70 in^2 compare to 5.43 in^2.

IV. Conclusion

Based on this case study, debutanizer column's case profile 4 which is of two-phase flow feed stream should be given more attention in sizing a PRV since it requires the biggest area for both PRV 1 and 2, which is 19.34 in^2 for two-phase PRV inlet and 12.70 for liquid PRV inlet. During the calculation, the sizing for both PRV 1 and 2 are very much dependent on the values of incoming mass flux as correction factor values kd, kc and kb are kept constant for each debutanizer column's case profiles. Result shows that lower sizing of PRV required higher values of mass flux.

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