MOMENTUM CHANGE IN DIGESTION RELIEF HEADERS

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Abstract

This paper discusses and demonstrates a method developed in engineering design for sizing of the relief header, and stress analysis of the header. The Leung's Omega calculation is used to size the header. An in-house, two-phase flashing flow, slip model predicts the force arising for a change in momentum with respect to time.

Stresses within the header pipework is analysed by use of available commercial software (e.g. CAESAR II and AutoPIPE). The analysis shows that the transmitted reaction force is up to 22% higher than the steady state load. This result is based on a relief header size that provides a relief flow rate of 1000 kg/s with a backpressure at the relief valve discharge of 30% of the set pressure. The contribution from momentum forces on the overall piping system can cause a multiplied effect of up to 2 times in comparison with the static case (without considering momentum forces).

NOTATIONS

A — Area (m^2)
C_P — Specific heat (J/kg K)
D — Pipe diameter (m)
F — Force (N)
f — Friction factor
G — Mass flux ($kg/s.m^2$)
g — Specific gravity (m/s^2)
h_{fg} — Latent heat of vaporization (J/kg)
K_{eq} — Equivalent fitting friction coefficient
L — Pipe length (m)
$\dot{m}$ — Mass flow rate (kg/s)
P — Pressure (Pa)
S — Slip ratio
T — Temperature (^oC)
V — Velocity (m/s)
ν — Specific volume (m^3/kg)
η — Pressure ratio (P/P_o)
x — Quality or vapour fraction
ρ — Density (kg/m^3)
θ — Angle (^{o})
ϕ^2 — Two-phase multiplier
ψ — Omega parameter

Subscripts

fg — Difference between vapour and liquid properties
g — Gas or vapour
L — Liquid
o — Stagnation inlet condition
V — Vapour
x, y — Direction

1. Introduction

Pressure relief systems are an integral aspect of safe digestion design and operation. Relief events from operating vessels can be erratic and irregular especially where vented slurry discharges through a vertical pipe. Any system carrying multi-phase fluids can experience slug flow. As the slugs of solids-liquid and puffs of vapour alternately enter the relief header, vibrations are felt and rumbling can be heard. The mixture velocity or density changes with time, and the momentum load at each bend (elbow or tee) will change concurrently. The momentum change leads to a dynamic load that may not be balanced within the system.

The dynamic load may change quickly with time and the pipe work may not have time to internally distribute the loads. Therefore forces and moments are not always balanced, which will be observed as pipe vibration. The internally induced loads can be higher than the applied loads.

A design backpressure of 10% of the set pressure had been used for alumina plants design in the past. Due to increased production demands, and the improvement of relief valve performance, the design backpressure of a relief header is reaching to 30% of the set pressure for bellowed valves and even more for pilot valves. The increased plant throughput, in comparison with the original design leads to an increase of the potential mass flow rate and the mixture velocity in the header. A significant increase of the momentum force may be the result during a relief event.

This paper discusses and demonstrates an engineering design method for sizing of the relief header, and stress analysis of the header pipework.

2. Method of Calculations

The calculations for designing of a relief header for an alumina digestion train are complex. The following main steps are generally involved.

- Determine the required relief capacity under the worse case conditions.
- Size the relief header.
- Calculate the reaction force at each bends.
- Analyse the stress of the header.

2.1 *Required Relief Capacity*

To determine the required relief capacity to cover all variations is impractical. Realistic emergency scenarios must therefore be individually examined to determine required relief valve capacities. Such scenarios usually assume a single incident, failure or error occurring at time zero. Events are not compounded unless one incident, failure or error cascades into another failure. More discussions on relief scenarios can be found from De Boer et al (2000) and Tran and Reynolds (1999).

2.2 *Sizing of Relief Header*

The Omega method in conjunction with the equivalent fitting friction coefficient is used in the momentum equation to determine the size of an inclined relief header (see figure 1) from the following integral equation (Leung; 1995, 1998):

$$K_{eq} = -\int_{\eta_1}^{\eta_2} \frac{[(1-\omega)\eta^2 + \omega\eta]\left(1 - G^2\dfrac{\omega}{\eta^2}\right)d\eta}{\dfrac{G^2}{2}[(1-\omega)\eta + \omega^2] + \eta^2\dfrac{\rho_o g L \sin\theta}{K_{eq}P_0}} \qquad (1)$$

where $\omega = \dfrac{x_o v_{go}}{v_o} + \dfrac{C_P T_o P_o}{v_o}\left(\dfrac{v_{fgo}}{h_{fgo}}\right)^2$

$\eta_1 = \dfrac{P_1}{P_o}$

$\eta_2 = \dfrac{P_2}{P_o}$

2.3 *Slip-flow model*

Several correlations for pressure loss in two-phase liquid-vapour systems have been proposed in the literature. Most of the correlations are based on the application of a momentum balance to a volumetric element of a pipe. Detailed derivations of the balance equations are given by Wallis (1969), Collier (1972) and Hewitt et al (1994). In terms of two-phase multiplier ϕ^2 and slip ratio S, the pressure drop can be estimated following the equation by Tran (2000):

$$-\frac{dP}{dz} = \Phi^2\left(\frac{2fG^2}{\rho_L D}\right) + \frac{\rho_V\rho_L[S(1-x)+x]}{x\rho_L + S(1-x)\ {}_V} g \sin\theta \qquad (2)$$

$$+\frac{d}{dz}\left\{G^2x^2\left[\frac{1}{\rho_V} + \frac{S(1-x)}{x\rho_L}\right] - G^2(1-x)\left[\frac{x}{\rho_V S} + \frac{(1-x)}{\rho_L}\right]\right\}$$

The terms on the right-hand side make up the slip flow model. The three terms describe frictional, gravitational and acceleration pressure gradients respectively.

2.4 *Reaction Force of a Reduced Tee*

The force of the fluid acting on a reduced tee (Figure 2) is determined from the steady flow momentum equation as follows:

$F_x =$

$$P_1A_1 + \dot{m}_1V_1 + (P_2A_2 + \dot{m}_2V_2 - P_3A_3 - \dot{m}_3V_3)\cos\theta \qquad (3)$$

$$F_y = (P_3A_3 + \dot{m}_3V_3 - P_2A_2 - \dot{m}_2V_2)\sin\theta \qquad (4)$$

3. Digestion Relief System

The slurry mixture of bauxite and caustic soda solution is pumped into high pressure reaction vessels or digesters. Steam is injected to maintain the required reaction temperature to produce a mixture of the dissolved alumina in caustic solution and undissolved bauxite solids. The discharge from these digesters is cooled to atmospheric boiling temperature by passing through a series of flash vessels. The steam evolved from these pressure vessels is used to pre-heat the incoming caustic liquor or bauxite slurry in heat exchangers.

The relief system for the Digestion plant generally consists of multiple pressure relief valves connected to each pressure vessel via a common header. The relief valves discharge via branch connections to a common relief line before entering a separator and atmospheric relief tank as shown in Figure 3.

4. Pipe Stress Analysis on Relief Header

Most piping systems are designed to handle single-phase fluids (uniformly liquid or gas). Under certain circumstances, however, the fluid may have multiple phases. For example, slurry systems transport solid materials in liquids, and gases may condense, creating pockets of liquid in otherwise gaseous media. Systems carrying multi-phase fluids are susceptible to slug flow.

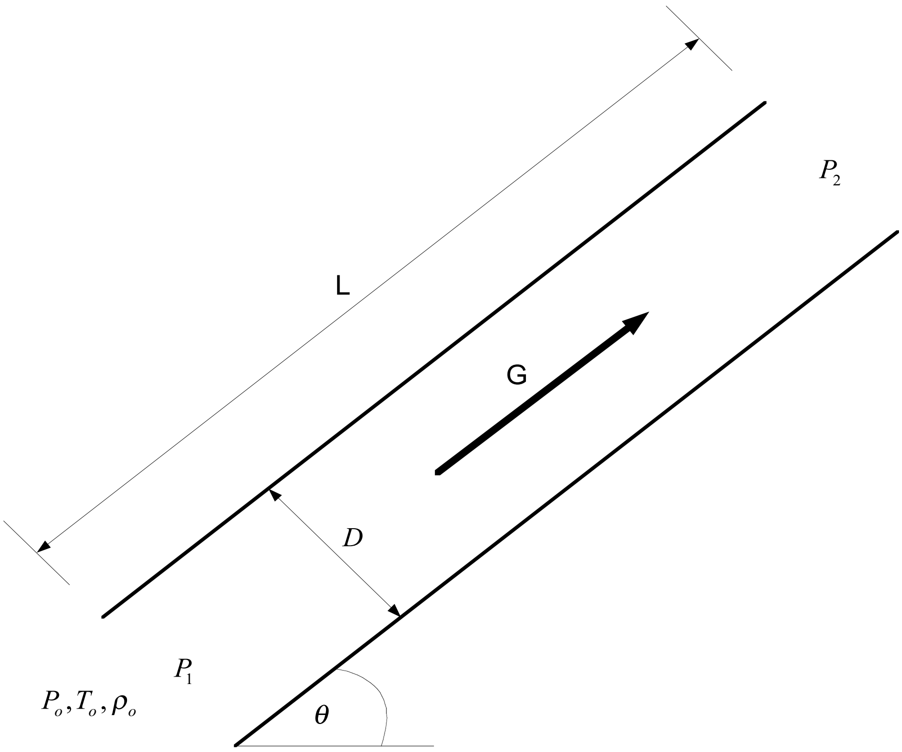

Figure 1 — Inclined discharge pipe.

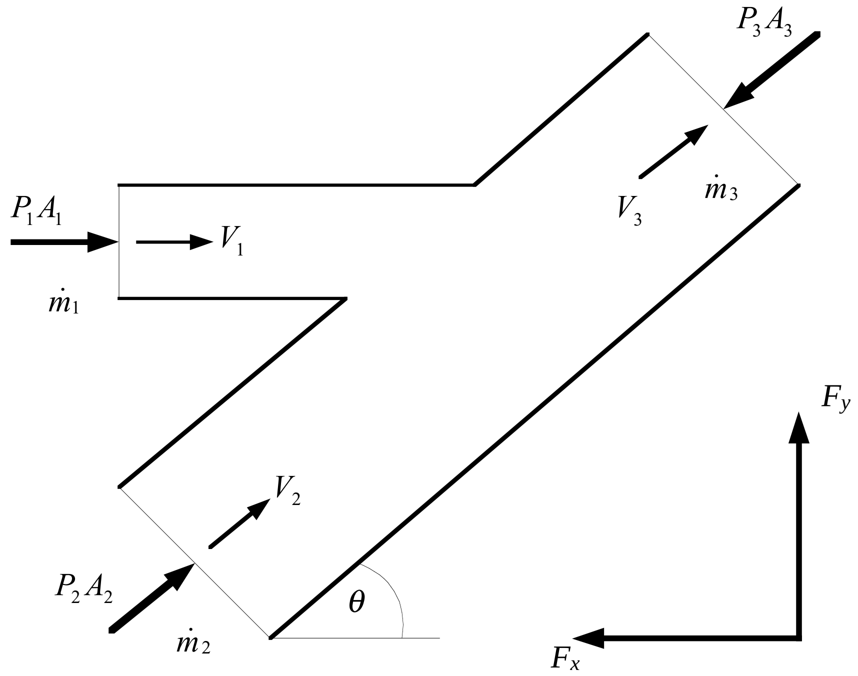

Figure 2 — The components of the fluid force on a reduced tee.

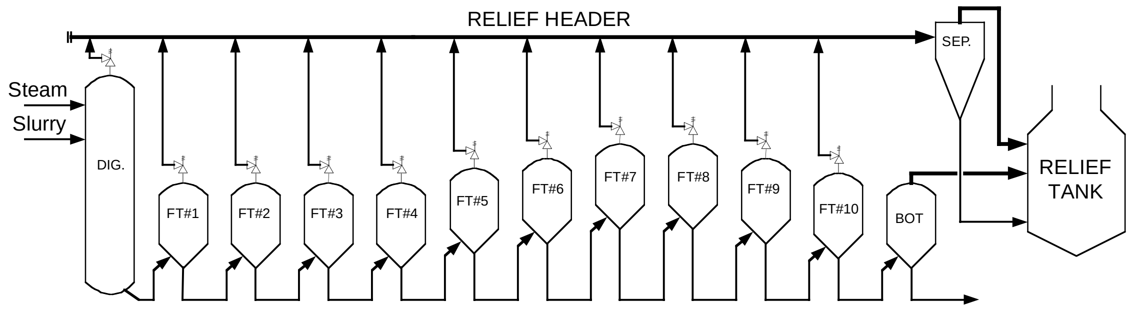

Figure 3 — Typical Digestion Relief System.

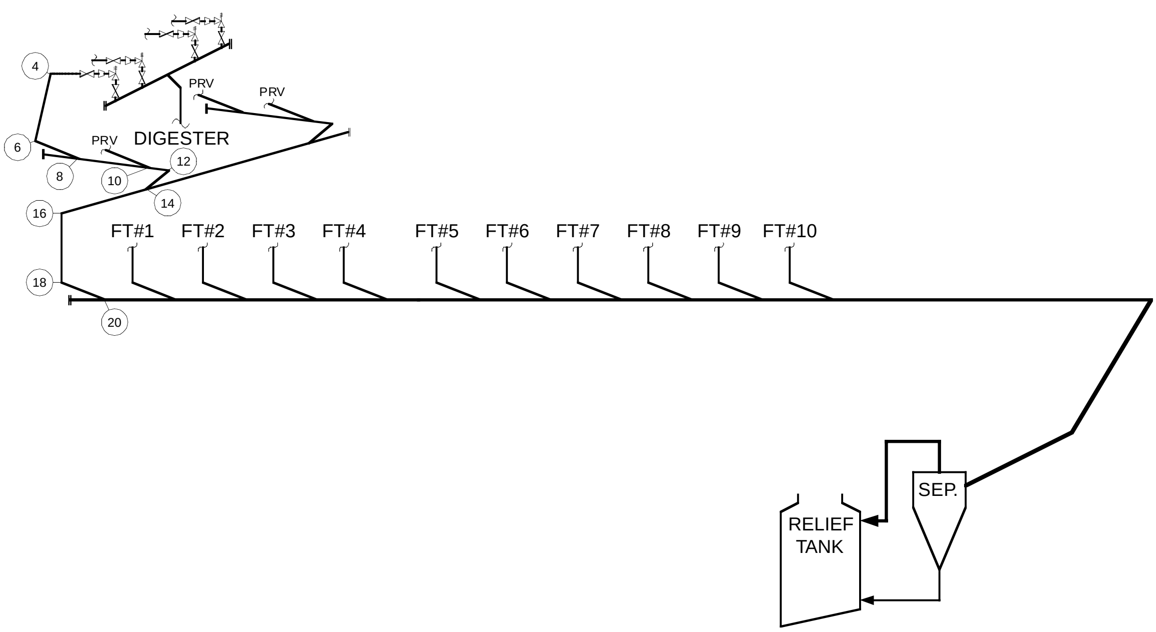

Figure 4 — Typical Digestion Relief Header.

Figure 4 shows a typical relief header configuration. Four relief valves 6″ × 10″ are installed on a digester to protect the overpressure. The relief valve outlet is increased to 350mm diameter via an expander to achieve the design backpressure. The relief valves are joined to the 1300mm main header via two sub-headers of 600mm and 900mm diameter.

In order to analyse the stress in the relief header piping the following assumptions are made:

- The required relief capacity is 1000kg/s.
- The digester set pressure is 5068 kPag.
- The backpressure is 30% of the set pressure.
- The digester temperature is 250ºC.

The software used for the pipe stress analysis is CAESAR II by COADE. The pipe stresses are reported for the sustained and expansion load cases for compliance with the appropriate design code.

The next step is solving for slug flow dynamic displacements using force spectrum analysis. The reaction forces on the relief header are estimated from the in-house two-phase flashing flow program (Tran, 2000). Force-time profile estimates for each elbow/elbow pair are obtained and then used to find the Dynamic Loading Factor (DLF) using the DLF spectrum generator. This spectrum represents the maximum ratio of dynamic and static displacements.

The unbalanced load on supply side is caused by pressure fluctuation due to quick opening or closing of valve/pump. The unbalanced load on discharge side is caused by vapour implosion (which is the difference between line pressure and vapour pressure). This load lasts only as long as it takes for the slug to traverse the elbow, and then suddenly drops to near zero again. The time duration of the load depends upon the length of the slug divided by the velocity of the fluid.

The loading between elbow/elbow pair due to change in momentum over time is determined from the following equation:

$$F = \rho \upsilon^2 A \sqrt{2(1-\cos\theta)} \tag{5}$$

Table 1 shows a comparison of the momentum force against the pressure force at each critical element in figure 4. These momentum forces will be used in the dynamic slug analysis of the relief header piping.

The ratio of momentum force and pressure force in Table 1 ranges from 9% to 22%. These ratios depend on the pipe size, relief capacity, backpressure of the header and the configuration of the piping system.

The results from the pipe stress analysis is summarized in Table 2:

Table 2 — Summarised results

Analysis Type	Maximum Stress as % of Allowable for Entire Piping System
Static — Sustained	45.08
Static- Expansion	54.72
Dynamic — Worse Case	106.1

The analysis indicates stresses contributed from the momentum forces of up to 22% in comparison with the pressure forces. The unbalanced force due to slug flow on the overall piping system can cause a multiplied effect of up to 2 times in comparison with the static case (without considering momentum forces).

If high stress regions exist in a piping system from dynamic loadings, it is recommended that the problem be resolved by mean of increasing the pipe thickness or by adding heavier support or thicker reinforcement pad. The location and type of supports in the vicinity of the high stress area can be modified to redirect loadings.

Other systems such as interconnecting piping from digesters to flash tanks, flash tank to flash tank, or applications with sudden opening or closing of control valves are susceptible to changes in momentum in the flow. These dynamic flow conditions can result in unbalanced forces and will lead to overstressing of the piping system.

5. Conclusions

Results from the above analysis indicate the importance of two-phase flow calculations in a relief header dynamic flow system. Changes in momentum flow between elbow pairs can cause excessive dynamic stresses.

Existing alumina refineries around the world are tending to increase their production to cater for higher demand. Relief piping may experience up to 30% of back-pressure compared to the original design condition of only 10%. Adequate analysis to prove the integrity of the piping system for the safety and well being of the process technicians is increasingly important and to meet Statutory Requirements.

Future relief system designs are expected to require accurate design methodology to ensure reliable and safe operation particularly during upset events.

Table 1 — Comparison between the momentum force and the pressure force

Element Number	Pressure Force (kN) — P		Momentum Force (kN) — M		% Comparison = M/P	
	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
4	119.04	125.4	12.69	11.78	10.7	9.4
6	109.65	116.65	14.21	13.04	13.0	11.2
8	—	108.88	—	10.27	—	9.4
10	—	108.88	—	14.34	—	13.2
12	264.32	274.45	25.42	24.27	9.6	8.9
14	—	264.08	—	25.47	—	9.7
16	392.24	414.39	74.06	69.66	18.9	16.8
18	367.71	391.36	79.46	74.26	21.6	19.0
20	—	367.08	—	79.56	—	21.7

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