

**A NEW APPROACH TO DESIGNING CENTRIFUGAL COMPRESSOR SURGE CONTROL SYSTEMS**

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**ABSTRACT**

Many facilities employ two or more centrifugal compressors, operated in either series or parallel configurations. An accurately designed surge control system that includes multiple compressors with the associated piping systems is a vital element of a facility's design and ongoing operational

integrity. The design must ensure compressors are not subjected to damaging fast dynamic events leading to large capital costs and significant down time for operators. Examples of such fast dynamic events are those following emergency shutdown (ESD) of fast stop of one or all compressor units in a station. Typical studies are not accurate enough to capture the complex interactions leading to

catastrophic events, especially for complicated system arrangements.

This paper introduces three methods of surge control analysis that can be conducted to assess the effectiveness of any surge control system design to prevent the compressor from surge. The first method utilizes the perturbation theory to relate the compressor deceleration and the resulting drop in its flow and head to determine the elapsed time that the compressor can stay out of surge before the surge control system brings about enough positive flow to prevent the unit from undergoing deep surge. The second method is simpler, and is based on a dimensionless number, called the inertia number, which combines the salient parameters from the dynamic equation between the fluid energy and that of the compressor rotor inertia to determine, as a first cut check, if the surge control system is adequate. The third method, which is always recommended, and is based on solving the full gas dynamic partial differential equations (PDEs) in spatial and temporal domain, which describe the true dynamic characteristics of the flow through the various piping elements, the compressor itself, to provide much more accurate predictions of surge control system behavior during fast transient events.

Comparisons are made to field measurements to provide model validations, and an example application (Case Study) of three units operating in parallel. The first two (Units 6 and 7) were existing in a compressor station, while the third (Unit 8) was an add-on. The addition of Unit 8 meant a number of station layout modifications, which included: re-wheeling of Units 6 and 7 (i.e., change the compressor impellers); adding after gas cooling; and relocating the anti-surge valves downstream of the coolers to allow for both hot (fast stop) and cold recycle (anti-surge) capabilities. Due to the addition of equipment and significant reconfiguration of station piping and valves, a dynamic surge analysis on Units 6, 7, and 8 was required to determine whether the existing anti-surge and fast stop valves were adequately sized and whether the anti-surge valves could be relocated downstream of the gas coolers. A new fast stop recycle system was added along with Unit 8, which also needed to be adequately sized. Further complications arose from the fact that Unit 6's anti-surge valve configuration differs from that of Unit 7 and that Unit 6 has twin recycle valves jointly serving as anti-surge valves with a single fast stop valve while Unit 7 has a single anti-surge valve and a single fast stop valve.

## NOMENCLATURE

$A$	- pipe cross-section area
$c$	- speed of sound
$c_1$	- speed of sound at suction condition
$c_2$	- speed of sound at discharge condition
$C_v$	- gas specific heat at constant volume
$D$	- pipe internal diameter
$D_o$	- impeller outer (tip) diameter.
$D_i$	- impeller average inlet diameter.

$E$	- friction and heat transfer source term in the energy equation
$f_{DW}$	- Darcy-Weisbach friction factor
$g$	- acceleration of gravity
$H_o$	- compressor head at steady state point
$H_a$	- compressor adiabatic head at any given inlet flow ( $Q_a$ )
$H_z$	- compressor adiabatic head at zero flow $= \alpha \sum_1^n U_i^2$
$H_s$	- compressor head at surge point at the current running speed.
$I$	- compressor/driver combined inertia
$k$	- isentropic exponent of the gas
$\dot{m}$	- gas mass flow rate through the compressor
$N$	- compressor speed
$N_I$	- inertia number
$P$	- pressure
$P_1$	- suction static pressure
$P_2$	- discharge static pressure
$Q$	- flow
$Q_a$	- compressor actual inlet flow.
$Q_s$	- compressor actual inlet flow at surge point at the same speed.
$R$	- gas constant
$t$	- time
$T$	- gas temperature
$T_a$	- surrounding (ambient) temperature
$T_1$	- suction gas temperature
$u$	- gas mean flow velocity
$U_h$	- overall heat transfer coefficient between fluid and surrounding
$U_i$	- rotational tip velocity of impeller (i).
$x$	- spatial length along a pipe
$( )_v$	- derivative at constant volume
$( )_s$	- derivative at constant entropy
$Z_{av}$	- average gas compressibility factor
$\alpha$	- zero flow head coefficient (equal to 1.0 for loss free impeller, and approx. equal to 0.4-0.6 to account for losses).
$\beta$	- friction and elevation source term in the momentum equation
$\gamma$	- parameter = $0.5 (H_s - H_o)$
$\phi$	- thermodynamic derivative (dimensionless)
$\eta_a$	- compressor adiabatic efficiency
$\eta_m$	- mechanical efficiency
$\rho_1$	- gas density at compressor inlet
$\rho$	- gas density
$\tau$	- pre-stroke delay plus pressure wave arrival time

## INTRODUCTION

Compression systems are employed in almost every stage of gas production, processing, transportation, storage and distribution facilities. They provide a vital function to the overall operation of these systems, and therefore, must be vigilantly monitored in order to ensure a high level of operational reliability. The majority of these compression systems employ centrifugal compressors, in either single- or multi-staged arrangements depending on the pressure ratio

requirements. They are driven by either gas turbines or electric motors with/without gearboxes. These compression systems are required to not only withstand uninterrupted operation for extended periods of time, but also be able to cope with flow and pressure transients associated with part-load operation, startup and emergency shutdown (ESD) [1-8].

During these transients, the centrifugal compressor may come close to or cross the surge limit, which could drive the compressor into deep surge, a violent instability that often damages the compressor itself, its bearing, seal, rotor assembly, and casing. Anti-surge systems are therefore employed to be activated to prevent the unit from undergoing surge. These anti-surge systems (or surge control systems) consist of one or two recycle lines around the compressor, which are equipped with fast acting valves that open when the compressor approaches the surge limit. When this happens, the compressor(s) interacts dynamically with system components around them, i.e. piping, fittings and equipment, drivers, as well as the associated control protocols [9-10].

Fluid inertias and compressor/driver rotor inertias play an important role in either stabilizing or destabilizing the system dynamics [11]. The compressors' performance characteristics also have an important role in the system dynamics behavior [12]. Ensuring reliable and safe operation of the various aspects of these compression systems requires a wholesome understanding of their dynamic behavior, which enables good system design, operation and control.

Several experimental and numerical investigations aimed at analyzing the dynamic interactions that take place between compression system components, particularly during ESD, have been reported, e.g. [13-17]. In these investigations, the surge model proposed by Greitzer and Moore [18,19] has been extended to centrifugal compressors. The method of characteristics for the solution of the governing one-dimensional equations of gas flow [20] has been proven to be adequate and correlates well with field measurements [12].

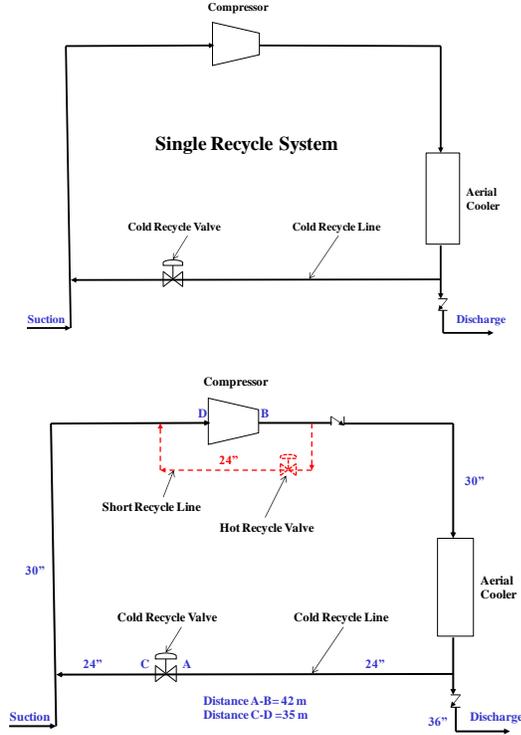
The modern surge control design process often involves analyses using the "lumped parameter" method of solving system ordinary differential equations (ODEs) which describe the gas dynamics, equipment, and control responses during a transient event. The lumped parameter method facilitates the selection of suitable components for a particular surge control system, or assesses the performance of an existing one. While this method provides reasonable approximations for simplified systems, it does not produce accurate representations for complex installations having several dissimilar compressors connected in parallel and series through complex suction and discharge piping systems. For such systems, a better approach is required to accurately assess the surge characteristics of the system, how the compressors interact, and protect the machinery from unexpected dynamic behaviors.

The present paper describes three methods for determining the effectiveness of any specific recycle system and recycle valve characteristics. These three methods are: i) a simplified method based on system impedance, ii) the concept of the Inertia number and iii) full dynamic simulation of the compression system.

## **FAST DYNAMIC EVENTS ASSOCIATED WITH ESD OR FAST STOP PROCESSES**

Of particular concern are the dynamics that occur following ESD, fast stop or power failure, as they represent the most severe and fast transients that could cause damage to the compressor unit and surrounding equipment. Parameters that affect the potential for the compressor to undergo surge during ESD are the recycle system gas volume, recycle valve characteristics such as maximum capacity, flow vs. opening characteristics, opening delay (i.e. the time between valve open solenoid drop out and the start of the valve stem movement on the valve – often called 'pre-stroke' delay), and valve travel time (i.e. the time taken for the valve to travel from closed to open positions – often called 'stroke' time) [14,15]. Additionally, timing of the compressor ESD signal, the fuel gas shutoff signal, fuel gas manifold size (in the case of gas turbine drivers), power train inertia, and the compressor's aerodynamic characteristics close to the surge point, all contribute to the complexity of the problem [11,12,16,17].

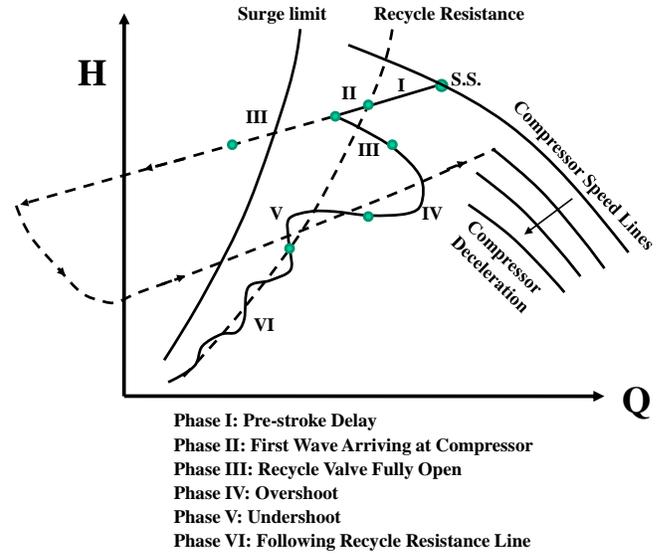
In the case of high pressure ratio (high head) multi-stage compressors, after coolers (typically aerial type) are often employed to bring the discharge gas temperature down to a level accepted for continuous operation of the downstream process and piping (set by the external coating maximum temperature limit). Two recycle systems are then contemplated: a) a single recycle system where the recycle path includes the aerial cooler as shown in Fig. 1 (top); and b) a dual recycle system where in addition to the aforementioned recycle system, another short-circuited system is employed specifically to deal with compressor surge control, as shown in Fig. 1 (bottom). In the dual recycle system, the longer recycle system is often called the cold recycle, as it re-circulates cooler gas downstream of the aerial cooler back to the compressor suction. The shorter recycle system is also called a hot recycle system for the opposite reason.



**Figure 1: Single vs. Dual Recycle Systems.**

The process of compressor station ESD is schematically depicted on a head-flow diagram in Fig. 2, following a trend observed both experimentally and numerically [11-13]. Six phases are identified as the compressor decelerates from a steady state point (S.S.) to zero flow and zero head across the compressor. Following an ESD, the operating point of the compressor follows approximately a straight line characterized by the slope ( $S$ ) for a period of time before any expansion or pressure waves arrive at the compressor outlet or inlet, respectively, as a result of opening the recycle valve. This period corresponds to the recycle valve pre-opening (pre-stroke) delay, which is a combined effect of a process signal delay and inherent mechanical delay in opening of the recycle valve once an ESD signal is issued. During this phase (Phase I), although the driver power is assumed to be completely shut-off, the compressor continues to rotate due to the combined inertia of its shaft, impeller and driver. The compressor decelerates due to the head across it, windage, friction, etc., according to the balance of the following equation:

$$\dot{W}_{driver} = I_{driver} \cdot N_{driver} \cdot \frac{dN_{driver}}{dt} + I_c \cdot N_c \cdot \frac{dN_c}{dt} + \frac{\dot{m} H_a}{\eta_a \eta_m} + \text{Windage \& Losses} \quad (0)$$



**Figure 2: Schematic of the Various Phases of an ESD Process Tracked on a Compressor Performance Characteristics (Wheel Map).**

In the above equation, it is assumed that the driver power was set to zero instantaneously at the instant of ESD. While this is correct for cases where electric motors are used as drivers, it is not absolutely correct for cases with gas turbine drivers. White and Kurz [16] have shown that one of the key problems is that there is residual power from the gas turbine even after the fuel is shut off. This is due to two effects: one is that there is always some fuel gas remaining in the fuel gas manifold system which will continue to feed the gas turbine combustor and hence sustain power for a few hundred milliseconds; and secondly, the rotor inertia of the gas generator itself will continue to provide hot gas to the power turbine even at a decreasing temperature. These effects can be mathematically represented by describing the power term on the left hand side of Eq. (0),  $\dot{W}_{driver}$ , as a declining function of time instead of setting it to zero at the instant of ESD. Similar treatment can be adopted to steam turbine drivers.

Once the recycle valve opens, a pressure wave travels downstream of the valve along the low pressure part of the recycle line and along the main suction line, while an expansion wave travels upstream of the valve along the high pressure part of the recycle line and along the main discharge line. The first wave to arrive at the compressor suction or discharge sides depends on the distance, which either wave needs to travel, and the local speed of sound along the corresponding path. The time taken for either wave to arrive first to the compressor determines the duration of Phase II shown in Fig. 2. Once this wave arrives at the compressor, the flow starts to increase through the compressor and head decreases, and hence the beginning of Phase III. The slope of the characteristic line shown in Fig. 2 ( $S=dH/dQ$ ), can be determined from the perturbation theory since small pressure

perturbation is related to local velocity perturbation by the characteristic impedance of the gas on either side of the compressor, that is:

On the suction side of the compressor:

$$\delta P_1 = -\frac{\rho_1 c_1}{A_1} \delta Q \quad (1)$$

and on the discharge side:

$$\delta P_2 = \frac{\rho_2 c_2}{A_2} \left( \frac{\rho_1}{\rho_2} \right) \delta Q = \frac{\rho_1 c_2}{A_2} \delta Q \quad (2)$$

Following the expression of the isentropic head in terms of the pressure ratio across the compressor in the form:

$$H = \xi \left[ \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right] \quad (3)$$

$$\text{where: } \xi = \frac{Z_{av} RT_1}{\left( \frac{k-1}{k} \right)}$$

The perturbation in  $H$  is related to the perturbation of  $P_1$  and  $P_2$  at a given operating condition corresponding to compressor head ( $H_o$ ) in the form:

$$\delta H = \left( \frac{k-1}{k} \right) (H_o + \xi) \left[ \frac{\delta P_2}{P_2} - \frac{\delta P_1}{P_1} \right] \quad (4)$$

The slope ( $S$ ) can then be determined from Eqs. 1, 2 and 4 as follows:

$$S = \frac{dH}{dQ} = \left( \frac{k-1}{k} \right) (H_o + \xi) \left[ \frac{\rho_1 c_1}{P_1 A_1} + \frac{\rho_1 c_2}{P_2 A_2} \right] \quad (5)$$

In Equation (5) above, when all parameters are in SI units, the units of the slope  $S$  will be (J.s/kg.m<sup>3</sup>). The recycle valve continues to open to the maximum open position resulting in further pressure waves and expansion waves arriving at the compressor suction and discharge sides, respectively. However, due to gas inertia in the recycle line and mainline, the flow through the compressor tends to overshoot as is manifested by Phase IV, followed by a short period of undershoot (Phase V) around the recycle system resistance line shown in Fig. 2. The final Phase VI is compressor wind down in which small over- and under-shootings around the recycle system resistance line occur until zero flow and zero

head are reached. Note that the recycle system resistance line is not the surge control line [20,21].

In the next Section, three methods are described that provide a basis for assessing the effectiveness and responsiveness of a given surge control system for a given compression train. These three methods vary in their complexity, whereby method III, which is based on solving the full governing dynamic equation in spatial and temporal domains, being the most complex but most comprehensive and accurate.

## EVALUATION OF THE RECYCLE SYSTEM DYNAMICS DURING ESD

Three methods will be applied here to assess the present surge protection system when an emergency shutdown (ESD) or fast-stop is initiated. These methods are:

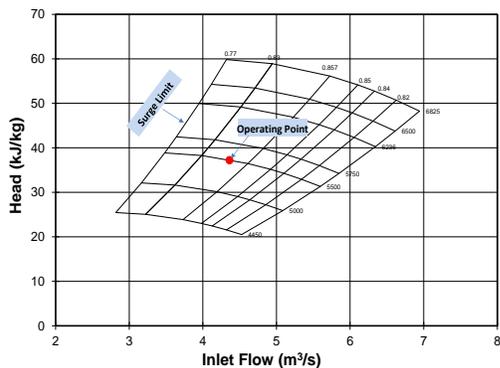
- Method I: Impedance Characteristics
- Method II: Inertia Number
- Method III: Full Dynamic Simulations.

### Method I: Impedance Characteristics

The basis for the impedance characteristics method follows the perturbation relationship between head and flow derived in the previous Section, resulting from the initial reduction in the flow through the compressor and the deceleration of the compressor rotor due to the exchange of the energy between the gas and the compressor rotor. If surge is to be prevented, the maximum allowable drop in the compressor speed before the arrival of either the first expansion wave to arrive at the compressor discharge flange or the compression wave to arrive at the compressor suction flange, both resulting from opening of the closest recycle valve, can be determined by running a tangent from the initial operating point with an impedance characteristics slope 'S' to the compressor characteristic at speed ( $N_o - \delta N_{max}$ ), as shown in Fig. 3. If the compressor speed drops below this limiting speed during ESD operation (as a result of e.g., low compressor inertia, an initial condition of high head, a late arrival of the first expansion wave to the compressor discharge or the pressure wave to the suction of the compressor), the compressor will undergo reverse flow (surge). This is because the compressor impeller at speeds slightly lower than ( $N_o - \delta N_{max}$ ) cannot sustain a positive flow against the prevailing high differential pressure (head) across it. In this case, the high differential pressure will drive reverse flow through the impeller while it is spinning forward. This is defined by the intersection of the characteristic line with the full compressor characteristic at the prevailing speed at this instant (point B in Fig 3), hence the development of the first surge cycle.



37.072 kJ/kg. Other relevant parameters required for the calculation of  $\delta t_{\max}$  in Eq. (11) are given in Table 1. The resulting  $\delta t_{\max}$  is calculated as 115 ms. According to the axial distances along the suction and discharge piping separating the cold recycle valve from the compressor (see Fig. 1-bottom), the arrival time of the expansion and pressure waves, along with valve pre-stroke delay are calculated in Table 2. These times are 296 ms and 288 ms, respectively. Clearly, the compressor in this case will undergo surge following an ESD operation since the time of arrival of either wave is much longer than  $\delta t_{\max}$  of 115 ms calculated above. In fact, the pre-stroke delay alone of this valve (=200 ms) is obviously too long to prevent the compressor unit from surging.

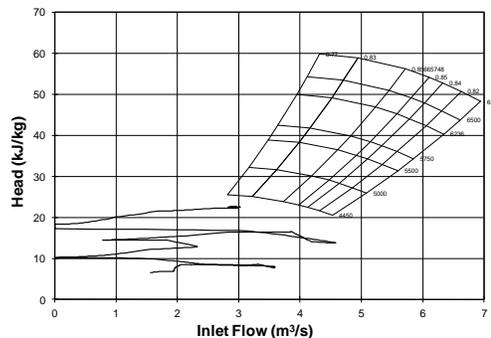


**Figure 4: Method I Example: Compressor Characteristics and Initial Operating Condition.**

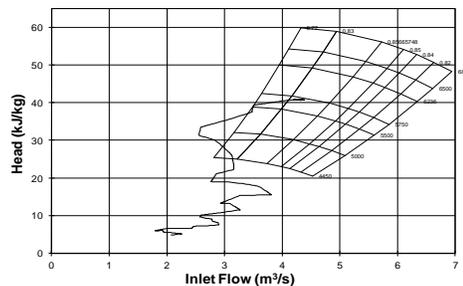
A field test of a fast stop at much lower speed and head was conducted on this compressor. At the time of the test, only the cold recycle was installed. The results of this test is shown in Fig. 5 indicating that the compressor has undergone several surge cycles as it was winding down following the fast stop. The initial steady state operating point for this test was  $Q_o = 3.0 \text{ m}^3/\text{s}$  and  $H_o = 22.5 \text{ kJ/kg}$ . Other relevant parameters required for the calculation of  $\delta t_{\max}$  in Eq. (11) are given in Table 2. Again, the compressor in this case has undergone surge following a fast stop since the time of arrival of either wave is much longer than  $\delta t_{\max}$  of 102 ms calculated in Table 3.

The obvious solution is not only to employ a recycle valve that has a shorter pre-stroke delay, but to have it located very close to either compressor discharge (preferable) or suction sides. This means, a dual recycle system is required, i.e. the addition of a short (hot) recycle system as shown in Fig. 1-bottom (dotted line). Again, the function of the short recycle system is for surge protection during ESD or fast stop, while the cold recycle system which includes the aerial cooler in the recycle path, is for unit startup and part load operation. A hot recycle was subsequently sized and installed around this compressor, and another field test was performed from an initial condition

shown in Fig. 6 and Table 3. Test results are also shown in Fig. 6 indicating that the compressor was driving toward surge but, due to the close proximity of the hot recycle to the compressor discharge (5 m on the discharge side) and that the hot recycle valve pre-stroke delay was shortened to 120 ms, the compressor was prevented from going into deep surge. The corresponding Method I calculations for this case are given in Table 4 showing  $\delta t_{\max} = 125 \text{ ms}$ , and time for the arrival of the first expansion wave to the compressor discharge flange is 131.88 ms (Table 5).



**Figure 5: Field Measurements of Compressor Fast Stop Using Cold Recycle System.**



**Figure 6: Field Measurements of Compressor Fast Stop Using both Cold and Hot Recycle Systems.**

**Table 1: Method I Example Calculation for the Cold Recycle System Only and Initial Operating Point Shown in Fig. 4.**

<b>Flow Conditions:</b>	
Suction Pressure	8202 kPa-a
Suction Temperature	283 K
Discharge Pressure	11352 kPa-a
Discharge Temperature	314 K
Average Compressibility	0.817
Molecular weight	17.953 kg/kmol
Suction Density	76.560 kg/m <sup>3</sup>
Isentropic Exponent	1.482
Isentropic Efficiency	0.8
Mechanical Efficiency	0.96
Gas Constant	463.098 J/kg.K
$C_1$	398.390 m/s
$C_2$	419.643 m/s
Suction Pipe Size	
Internal Diameter	0.737 m
X-Sectional Area ( $A_1$ )	0.426 m <sup>2</sup>
Discharge Pipe Size	
Internal Diameter	0.737 m
X-Sectional Area ( $A_2$ )	0.426 m <sup>2</sup>
<b>Operating Point</b>	
$Q_o$	4.363 m <sup>3</sup> /s
$H_o$	37072 J/kg
$Q_{so}$	3.482 m <sup>3</sup> /s
$H_{so}$	38863 J/kg
$N_o$	5500 RPM
$\omega$	575.959 rad/s
Inertia	117 kg.m <sup>2</sup>
<b>Results of Simple Approach :</b>	
$(k-1)/k$	0.325
$\xi$	329625.404 J/kg
$S$	1831.540 (J.s/kg.m <sup>3</sup> )
$dN_{max}/N_o$	0.048
$dN_{max}$	262.447 RPM
$d\omega$	27.483 rad/s
$\frac{\dot{m}_o H_o}{\eta_a \eta_m}$	16124.062 kW
$\delta t_{max}$	0.115 s
$\delta t_{max}$	115 ms

**Table 2: Time for the Expansion and Compression Wave to Arrive at the Compressor Outlet and Inlet Respectively, from the Cold Recycle Valve.**

Valve Pre-stroke delay	200 ms
Discharge Piping Length	42 m
Expansion Wave Arrival Time	100.09 ms
Combined Time	300.09 ms
Suction Piping Length	35 m
Pressure Wave Arrival Time	87.85 ms
Combined Time	287.85 ms

**Table 3: Calculation for the Field Measurement Case of Fig. 5.**

<b>Flow Conditions:</b>	
Suction Pressure	8202 kPa-a
Suction Temperature	283 K
Discharge Pressure	9340 kPa-a
Discharge Temperature	298 K
Average Compressibility	0.824
Molecular weight	17.953 kg/kmol
Suction Density	75.951 kg/m <sup>3</sup>
Isentropic Exponent	1.482
Isentropic Efficiency	0.8
Mechanical Efficiency	0.96
Gas Constant	463.098 J/kg.K
$C_1$	399.985 m/s
$C_2$	410.449 m/s
Suction Pipe Size	
Internal Diameter	0.737 m
X-Sectional Area ( $A_1$ )	0.426 m <sup>2</sup>
Discharge Pipe Size	
Internal Diameter	0.737 m
X-Sectional Area ( $A_2$ )	0.426 m <sup>2</sup>
<b>Operating Point</b>	
$Q_o$	3 m <sup>3</sup> /s
$H_o$	22500 J/kg
$Q_{so}$	2.8 m <sup>3</sup> /s
$H_{so}$	23500 J/kg
$N_o$	4000 RPM
$\omega$	418.879 rad/s
Inertia	117 kg.m <sup>2</sup>
<b>Results of Simple Approach :</b>	
$(k-1)/k$	0.325
$\xi$	332270.665 J/kg
$S$	1905.279 (J.s/kg.m <sup>3</sup> )
$dN_{max}/N_o$	0.033
$dN_{max}$	132.586 RPM
$d\omega$	13.884 rad/s
$\frac{\dot{m}_o H_o}{\eta_a \eta_m}$	6675.375 kW
$\delta t_{max}$	0.102 s
$\delta t_{max}$	102 ms

**Table 4: Calculation for the Field Measurement Case of Fig. 6.**

<b>Flow Conditions:</b>	
Suction Pressure	8202 kPa-a
Suction Temperature	283 K
Discharge Pressure	11450 kPa-a
Discharge Temperature	316 K
Average Compressibility	0.817
Molecular weight	17.953 kg/kmol
Suction Density	76.560 kg/m <sup>3</sup>
Isentropic Exponent	1.482
Isentropic Efficiency	0.8
Mechanical Efficiency	0.96
Gas Constant	463.098 J/kg.K
$C_1$	398.390 m/s
$C_2$	420.977 m/s
Suction Pipe Size	
Internal Diameter	0.737 m
X-Sectional Area ( $A_1$ )	0.426 m <sup>2</sup>
Discharge Pipe Size	
Internal Diameter	0.737 m
X-Sectional Area ( $A_2$ )	0.426 m <sup>2</sup>
<b>Operating Point</b>	
$Q_o$	4.39 m <sup>3</sup> /s
$H_o$	40160 J/kg
$Q_{so}$	3.62 m <sup>3</sup> /s
$H_{so}$	42900 J/kg
$N_o$	5700 RPM
$\omega$	596.903 rad/s
Inertia	117 kg.m <sup>2</sup>
<b>Results of Simple Approach :</b>	
$(k-1)/k$	0.325
$\xi$	329625.404 J/kg
$S$	1842.649 (J.s/kg.m <sup>3</sup> )
$dN_{max}/N_o$	0.053
$dN_{max}$	299.577 RPM
$d\omega$	31.372 rad/s
$\frac{\dot{m}_o H_o}{\eta_a \eta_m}$	17575.248 kW
$\delta t_{max}$	0.125 s
$\delta t_{max}$	125 ms

**Table 5: Time for the Expansion and Compression Wave to Arrive at the Compressor Outlet and Inlet Respectively, from the Hot Recycle Valve.**

Valve Pre-stroke delay	120 ms
Discharge Piping Length	5 m
Expansion Wave Arrival Time	11.88 ms
Combined Time	131.88 ms
Suction Piping Length	15 m
Pressure Wave Arrival Time	37.65 ms
Combined Time	157.65 ms

### **Method II: Inertia Number**

Following numerous analyses conducted on different design philosophies of compression systems, and incorporating different types of centrifugal compressors, the decision to employ a short recycle system around the compressor unit to overcome the possibility of surging the unit during ESD operation lies in the balance between the following parameters:

- Effective compressor/driver rotor inertia defined at the compressor end, ( $I$ ).
- Maximum compressor speed ( $N$ ).
- The delay time before the recycle valve starts its opening stroke plus time taken for the first expansion wave or pressure wave to arrive at the compressor outlet or inlet, respectively, due to first crack-opening of the recycle valve ( $\tau$ ).
- The maximum fluid energy extracted from the compressor/driver power trains; which can be approximated by the product, where subscript ( $so$ ) refers to conditions at the surge point and at the same maximum compressor speed.

A non-dimensional number was derived [17,20] that includes all of the above independent parameters. This dimensionless number, herein referred to as the Inertia number ( $N_I$ ), is defined as:

$$N_I = \frac{I N^2}{\dot{m}_{so} H_{so} \tau} \quad (12)$$

A threshold value of ( $N_I$ ) was found from actual installations and dynamic analyses conducted on 24 industrial compression systems employing different compressor models and station design. This threshold value was found to be  $\sim 30$ , below which a shorter recycle system would definitely be needed to prevent the compressor unit from undergoing surge during ESD operation. When the Inertia number is greater than 100, a single recycle system (as shown in top of Figure 1) would be adequate. For an Inertia number ( $N_I$ ) in the range of 30-100, detailed dynamic simulation on the station should be conducted (i.e. Method 3). Table 6 gives the various operating and design parameters for those 24 industrial compression systems analyzed and the respective Inertia number ( $N_I$ ) based on a value of  $\tau$  corresponding to the cold recycle system. Note that consistent SI units should be used to calculate ( $N_I$ ). The comment column in Table 6 indicates whether the design incorporated a short (hot) recycle or not.

Station #8 shown in Table 6 is the example used in Method I above. It is shown that at 6,500 RPM, corresponding inertia and  $\dot{m}_{so} H_{so}$ , the inertia number is 14.7, which is less than the threshold value of 30 discussed above. Therefore, it is pointing to the fact that the cold recycle system alone will not be adequate in protecting the compressor unit from surging during an ESD or fast stop.

**Table 6: Inertia Numbers of 24 Industrial Gas Compressor Stations and Comparison with the Present Compressor Station.**

Station	I (kg.m <sup>2</sup> )	N (RPM)	Flow (kg/s)	Hso (J/kg)	$\tau$ (ms)	No of Stages	Cooler	Inertia Number	Comment
1	36.1	6800	250	28000	200	1	No	13.1	Delay in Fuel Gas by 100 ms
2	33.7	8856	143	80600	200	2	Yes	12.6	Hot & Cold Recycle Installed
3	32.2	7780	125	64500	200	2	Yes	13.3	Hot & Cold Recycle Installed
4	56.5	6500	180	52000	200	2	Yes	14.0	Hot & Cold Recycle Installed
5	41.5	6671	150	40000	200	2	Yes	16.9	Hot & Cold Recycle Installed
6	243.6	6100	299	68772	200	2	Yes	24.2	Hot & Cold Recycle Installed
7	259.6	4250	380	26220	200	1	Yes	25.8	Hot & Cold Recycle Installed
8	117.0	6500	244	52625	288	2	Yes	14.7	Hot & Cold Recycle Installed
9	102.5	6000	35	160000	215	6	Yes	33.6	Hot & Cold Recycle Installed
10	113.5	6825	420	31000	588	1	Yes	7.6	Hot & Cold Recycle Installed
11	3.9	11967	3	117000	337	4	Yes	54.0	Hot & Cold Recycle Installed
12	6.1	11970	9	124386	324	4	Yes	27.6	Hot & Cold Recycle Installed
13	104.8	7850	51	160612	368	5	Yes	23.4	Hot & Cold Recycle Installed
14	94.3	8311	50	152825	368	6	Yes	25.3	Hot & Cold Recycle Installed
15	0.2	20000	20	32000	185	1	No	6.5	Hot Recycle
16	128.6	5194	480	32000	200	1	No	12.4	Hot Recycle
17	870.0	5775	350	39000	200	2	Yes	116.6	Only Cold Recycle
18	1.885	14000	5.00	154000	260.29	6	Yes	20.2	Hot & Cold Recycle Installed
19	29.86	8000	104.9	58400	200	2	Yes	17.1	Hot & Cold Recycle Installed
20	29.86	8000	58	59200	200	2	Yes	30.5	Hot & Cold Recycle Installed
21	24.6	9053	154	52130	190	2	Yes	14.5	Hot & Cold Recycle Installed
22	24.6	9500	155	56947.72	200	2	Yes	13.8	Hot & Cold Recycle Installed
23	147.3	5000	550	36400	200	2	Yes	10.1	Hot & Cold Recycle Installed
24	80.9	6400	550	25471	200	1	Yes	13.0	Hot & Cold Recycle Installed

### Method III: Full Dynamic Simulations

In a full numerical dynamic simulation of such compression systems, it is important to include the temporal-spatial dependence terms in all three governing equations for the gas flow in each piping element. In many of the commercial codes, only the time gradients are considered in the dynamic simulations, which amounts to describing the dynamics of the system using Ordinary Differential Equations (ODEs) that are much less rigorous than the Partial Differential Equations (PDEs). This is referred to as the ‘‘lumped parameter’’ method, which gives a solution that is a reasonable approximation of the distributed model solution. However, the lumped parameter approach is not adequate for dealing with compression dynamics involving recycle systems and phenomena of compressors going into, and out of, surge. The spatial gradients along the length of the pipe segments are crucial, as was determined from the previously discussed ‘‘Method I’’. The spatial gradients describe the time required for perturbations in pressure, flow and temperature to propagate from one point in the system to another.

The methodology in the dynamic simulations conducted here retains all terms in the one-dimensional governing PDE’s described below [17, 20 through 27]:

#### Continuity:

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial u}{\partial x} + u \frac{\partial \rho}{\partial x} = 0 \quad (13)$$

#### Momentum:

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \frac{\partial P}{\partial x} - \beta = 0 \quad (14)$$

#### Energy:

$$\frac{\partial P}{\partial t} + u \frac{\partial P}{\partial x} - c^2 \left( \frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} \right) - E = 0 \quad (15)$$

where;

$$\beta = - \left[ \frac{f_{DW}}{2D} \rho u |u| + \rho g \sin(\theta) \right] \quad (16)$$

$$E = \phi (q_h - u \beta) \quad (17)$$

$$\phi = \frac{\rho}{T} \left( \frac{\partial T}{\partial \rho} \right)_s = \frac{1}{\rho C_v} \left( \frac{\partial P}{\partial T} \right)_v \quad (18)$$

$$q_h = \frac{4U_h}{D} (T_a - T) \quad (19)$$

Note that the effects of both pipe wall friction and heat transfer with the surroundings are accounted for in the conservation of energy via the parameter,  $E$ , in Eq. (17). Using the method of characteristics, the above hyperbolic partial differential equations are transformed into ordinary differential equations, which lead to a set of algebraic compatibility equations along two characteristic lines and a particle path line [21]. These compatibility equations, together with the respective characteristic lines are integrated in the time-space domain. In the derivation of the finite-difference compatibility equations, the real gas assumption is introduced and GERG-2008 [28] equation of state is employed to specify the relation between the gas density, temperature, pressure and enthalpy, as well as to determine the physical and thermodynamic properties at each node in the system.

Similar governing equations describing the transient flows through physical components in the system are also formulated and combined with Eq. (13-15). These elements are throttle or pressure loss elements, combining and dividing tees, reducers or expanders, capacitance (plenum, volume, vessels), choked and un-choked valves, aerial coolers with a set duty or a set outlet temperature, etc. A full account of the governing equations for these elements is given in [22]. Throttle elements and capacitance elements are modeled based on quasi-steady state equations describing pressure changes as well as energy and mass balances across the element. These equations, when combined with the three compatibility equations for the pipes connected upstream and downstream of the element, are solved simultaneously to give the unknown variables on both sides of the element at each time step.

Different formulations of the equations are used to account for reversed flow situations.

The compressor itself is assumed to respond to any perturbation in a quasi-steady manner following its full characteristic curve, including that to the left of the surge limit [2,3,17,18]. At a given flow to the left of the surge limit, however, the actual head may differ from the steady state characteristics, which is the consequence of the compressor going into surge. A physically realistic and commonly used representation of this characteristic is that of a simple cubic given by the following equation [14,15]:

$$H_a = H_z + \gamma \left[ 1 + 1.5 \left( \frac{2Q_a}{Q_s} - 1 \right) - 0.5 \left( \frac{2Q_a}{Q_s} - 1 \right)^3 \right] \quad (20)$$

Where:

- $Q_a$  - compressor actual inlet flow.
- $H_a$  - compressor adiabatic head at any given inlet flow ( $Q_a$ )
- $H_z$  - compressor adiabatic head at zero flow =  $\alpha \sum_1^n U_i^2$
- $\gamma$  - parameter =  $0.5 (H_s - H_o)$
- $\alpha$  - zero flow head coefficient (equal to 1.0 for loss free impeller, and approx. equal to 0.4-0.6 to account for losses).
- $U_i$  - rotational tip velocity of impeller (i).
- $H_s$  - compressor head at surge point at the current running speed.
- $Q_s$  - compressor actual inlet flow at surge point at the same speed.
- $D_o$  - impeller outer (tip) diameter.
- $D_i$  - impeller average inlet diameter.

Compressor/driver dynamics are governed by Eq. (1); relating the driver power to the gas power and the inertias of both driver and compressor. It should be noted that the driver and compressor inertias should also include the inertia of the elements of the gearbox and couplings connected to either side, respectively. Additionally, in the case of a two-shaft gas turbine driver, the applicable driver inertia in Eq. (1) above is only the power turbine (i.e. the driver rotor) and coupling inertias and is not inclusive of the gas generator inertia.

Finally, a compression system consists of most of the elements described above, whether it is a pipe element, a connecting element or boundary condition. These constitute sets of highly non-linear equations, which must be solved simultaneously to determine the unknowns (pressure, mass flow rate and temperature). Each set of equations requires solution at each  $\Delta x$  location along each pipe element at each  $\Delta t$

time step. To achieve numerical stability, the Courant stability condition [29] is applied which stipulates that:

$$\Delta t \leq \frac{\Delta x}{C + v} \quad (21)$$

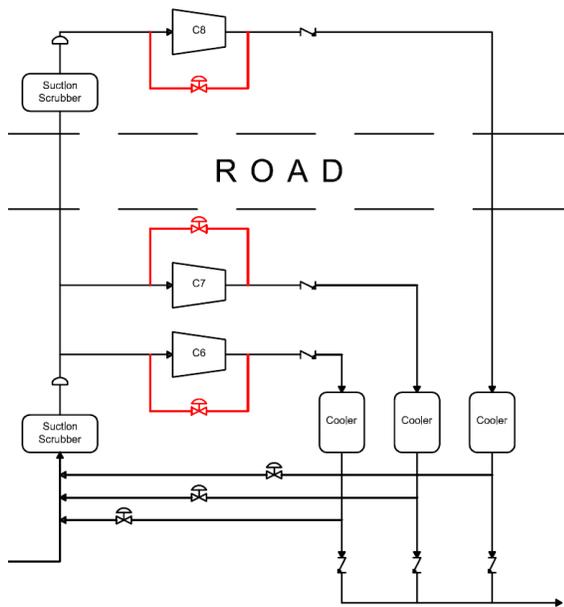
The Newton-Raphson method for the solution of non-linear equations is used because of its convergence speed and efficiency. The method is iterative in nature and solves all equations simultaneously. The starting point for a variable at a given time step is the value obtained as a solution from the previous time step. With small time steps (required by the stability condition), parameter changes longer than this time step will be captured and therefore transients occurring over several time steps will certainly be accounted for. Variables calculated at a given time step represent a good starting point for the next time step calculation. The iteration process within each time step is continued until the desired solution tolerance is achieved. Generally, the required calculation accuracy is obtained in under ten iterations at each time step.

Finally, at each time step, a set of **Mixed Algebraic and ODE's** equations (constituting a MAD set) which describe the governing equations of the connected control system. These equations are solved simultaneously at each time step in a different solver routine. The output from the control system solver is then fed to the gas dynamic solver described above and act as set points, constraints or boundary conditions.

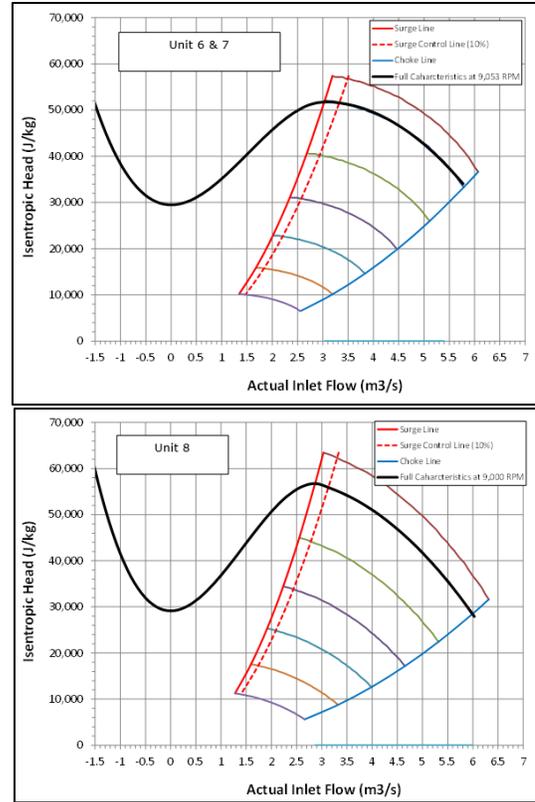
## CASE STUDY

This case study is an example of compression facility that employs 8 compressor units in total; Units 1 through 5 are slow speed integral compressors and Units 6 through 8 are gas turbine driven centrifugal compressors. Unit 8 is the latest addition to the station and operates in parallel with Units 6 and 7. The addition of Unit 8 meant a number of station layout modifications were necessary. These included: re-wheeling of Units 6 and 7 (i.e., change the compressor impellers); adding after gas cooling; and relocating the anti-surge valves downstream of the coolers to allow for both hot (fast stop) and cold recycle (anti-surge) capabilities. Due to the addition of equipment and significant reconfiguration of station piping and valves, a dynamic surge analysis on Units 6, 7, and 8 was required to determine whether the existing anti-surge and fast stop valves were adequately sized and whether the anti-surge valves could be relocated downstream of the gas coolers. A new fast stop recycle system was added along with Unit 8, which also needed to be adequately sized. Further complications arose from the fact that Unit 6's anti-surge valve configuration differs from that of Unit 7 and that Unit 6 has twin recycle valves jointly serving as anti-surge valves with a single fast stop valve while Unit 7 has a single anti-surge valve and a single fast stop valve.

Units 6 and 7 are similar OEM and model# compressors driven by gas turbines, while Unit 8 is a different OEM compressor also driven by a gas turbine. The combined rotor inertia of Unit 6 compressor/power turbine assembly (which is the same for the other two Units) is  $24.6 \text{ kg}\cdot\text{m}^2$ . The compressor performance characteristics (wheel maps) including the full characteristics to the left of the surge line are given in Fig. 8, respectively. The initial steady state operating points on the three Units are indicated on the respective wheel maps, and are also given in Table 7. The mixture composition of the gas flowing through the station is given in Table 8. Finally, the selected recycle valves (hot and cold) for the three Units are given in Table 9 along with the estimated pre-stroke delay and full-stroke opening time, respectively. Of notice is that the hot valve capacity is larger for Unit 8 than the that for Units 6 and 7 due to the relatively large volume of gas trapped between the hot recycle and check valves on the discharge side of Unit 8 (approx.  $13.7 \text{ m}^3$ ) vs. that on the discharge side of either of Units 6 or 7 ( $3.3 \text{ m}^3$  and  $5.7 \text{ m}^3$ , respectively).



**Figure 7: Schematic of the Case Study Involving Three Compressor Units Configured in Parallel Operation.**



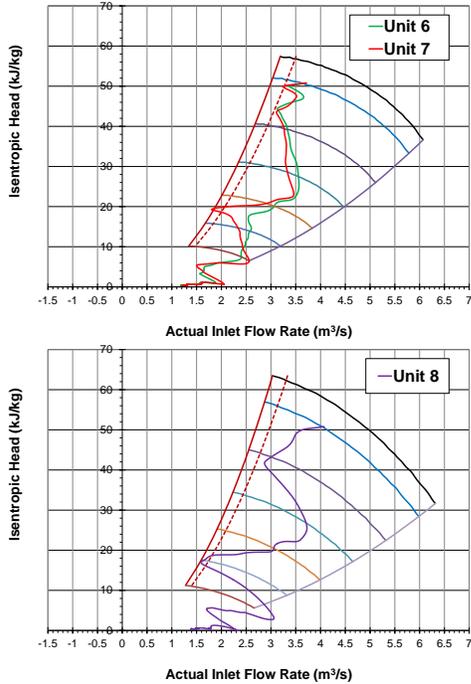
**Figure 8: Compressor Performance Characteristics of Units 6&7 (top) and Unit 8 (bottom) Showing Full Characteristics at one Speed and the Respective Initial Steady State Operating Point.**

**Table 7: Initial Steady State Operating Points of Units 6, 7 and 8.**

		Parallel		
		Unit 6	Unit 7	Unit 8
Suction Pressure	Ps (MPa-a)	5.598	5.597	5.597
Discharge Pressure	Pd (MPa-a)	8.168	8.168	8.169
Suction Temperature	Ts (°C)	10.0	10.0	10.0
Discharge Temperature	Td (°C)	48.9	48.9	47.9
Compressor Mass Flow Rate	mC (kg/s)	165.6	165.3	181.4
Compressor Actual Inlet Flow Rate	Qa (m3/s)	3.72	3.71	4.07
Compressor Isentropic Head	H (kJ/kg)	50.8	50.8	50.8
Compressor Speed	RPM	9,062	9,062	9,020

**Table 8: Gas Mixture Composition.**

	Mole %
METHANE	97.317
ETHANE	2.332
PROPANE	0.095
i-BUTANE	0.002
n-BUTANE	0.006
NITROGEN	0.203
CARBON DIOXIDE	0.045
Total	100.00



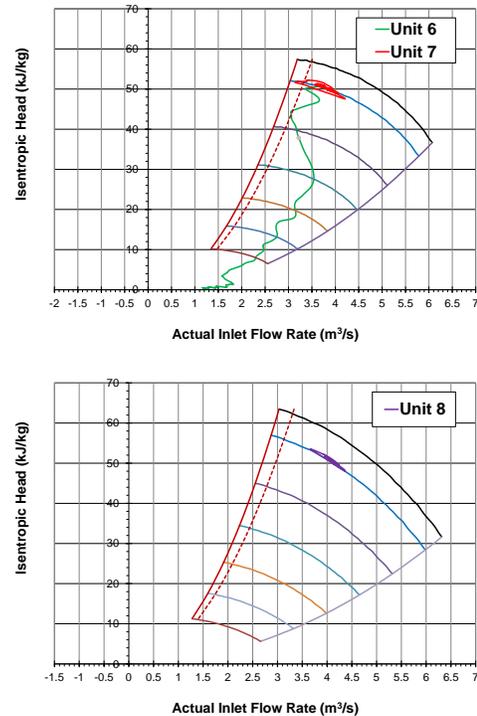
**Figure 9: Head-Flow Trajectories of the Three Units on the Respective Wheel Maps Following ESD or Fast Stop of All Three Units Simultaneously.**

**Table 9: Hot and Cold Recycle Valve Sizes, Trim Types and Capacities for the three Units.**

	Function	Location	Size	Cg	Trim	Pre-Stroke Delay (ms)	Full Stroke Time (ms)
<b>Unit 6</b>	Fast Stop Valve	Hot Recycle	8"	37,000	Quick Open	100	400
	Anti-Surge Valve	Cold Recycle	10"	44,000	Eq %	100	660
<b>Unit 7</b>	Fast Stop Valve	Hot Recycle	8"	37,000	Quick Open	100	400
	Anti-Surge Valve	Cold Recycle	10"	44,000	Eq %	100	660
<b>Unit 8</b>	Fast Stop Valve	Hot Recycle	8"	48,000	Linear	100	400
	Anti-Surge Valve	Cold Recycle	10"	48,000	Eq %	100	660

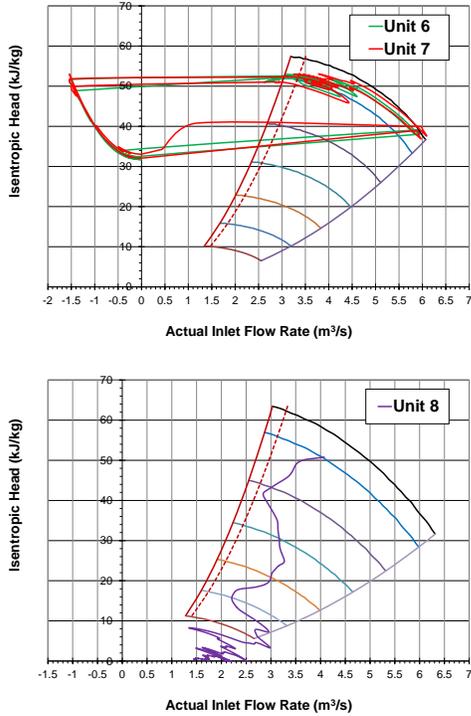
Dynamic simulations were conducted first to assess the adequacy of the selected recycle valves for preventing the Units from undergoing surge if all Units are subjected to an ESD or Fast Stop procedure. The results are shown in Fig. 9, which indicate a normal pattern of all units winding down along an H-Q path to the right of the respective surge lines. This is a good indication of the adequacy of the size, trim type and opening time characteristics of the selected valves. Note that, in the event of an ESD or Fast Stop, both hot and cold recycle valves around each Unit would open according to the opening time indicated in Table 9.

The question that arises is what happens if one Unit is subjected to ESD or Fast Stop, while the other two Units are kept running. Results of dynamic simulation of an ESD or Fast Stop operation of either Unit 6 or Unit 7, while keeping the other two Units running are shown in Fig. 10 (in this case, Unit 6 is selected to be ESD). Similar results were obtained if Unit 7 is selected to be ESD, since both Units 6 and 7 are alike. The results show that the two other Units that are kept running, were subjected to small disturbances but stayed on the same speed and discharge pressure control without being forced to go to surge.



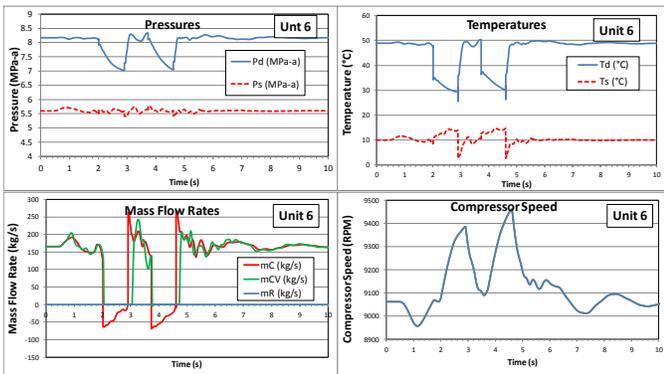
**Figure 10: Head-Flow Trajectories of the Three Units on the Respective Wheel Maps Following ESD or Fast Stop of Only Unit 6, While Units 7 and 8 Continue to Run.**

However, the situation is different when Unit 8 is subjected to ESD or Fast Stop while the other two identical ones Units 6 and 7 are kept running. The results of the dynamic simulation of this case are shown in Fig. 11, which shows that Unit 8 wound down surge free while both Units 6 and 7 have undergone two surge cycles, and each cycle would last approximately 0.8-0.9 s as shown in Fig. 12. These two surge cycles may be permissible since they are only two, and that two compressors recover back to normal operation.



**Figure 11: Head-Flow Trajectories of the Three Units on the Respective Wheel Maps Following ESD or Fast Stop of Only Unit 8, While Units 6 and 7 Continue to Run.**

It is interesting to observe that when either Unit 6 or 7 is subjected to ESD or Fast Stop operation, neither of the other running units are affected, but when Unit 8 is subjected to ESD or Fast Stop, the other two units would undergo two surge cycles. This is likely due to the fact Unit 8 is not in the same vicinity of Units 6 and 7. As it was a late add-on to the station, it was located across the road from Units 6 and 7 site with some distances between it and the original Units 6 and 7.



**Figure 12: Pressure-, Flow-, Temperature- and Speed-Time Profiles of the Running Unit 6 Flow Following ESD or Fast Stop of Unit 8, While Units 6 and 7 Continue to Run.**

## DISCUSSION

This paper can be useful to those in the industry not intimately familiar with surge design or analysis methods. Examples include Project Managers with backgrounds other than rotating equipment, Operations personnel, and other less technical positions. First, it describes what surge is, typical surge behavior, and why it is important to design a robust surge is control system. Additionally, this paper describes how surge can damage centrifugal compressors if a surge control system is inadequately designed. This is important as compressor repair and/or replacement costs can be exceedingly high as a result of lost down time (lost revenue), equipment and premium-time labor costs.

The methods given herein provide consideration to the spatial aspects of a particular system design that are not accounted for using lumped volume parameter methods. Each compressor installation has its own wheel maps, piping design and flow conditions, and therefore cannot be generalized by ignoring the spatial considerations (i.e. lengths of pipe). Doing so can lead to a false sense of security in the surge protection design for a given system.

Methods 1 and 2 provide tools to compressor system designers to 1) better determine whether the system in question requires a hot recycle system, 2) if the recycle systems as designed will be adequate in preventing surge, and 3) when a detailed dynamic simulation (Method 3) of the system is required. The tools can also be useful to end users, and EPC's desiring to check the adequacy of systems proposed by vendors.

In some cases surge cannot be avoided, and going into one surge cycle may be ok. Method 3 provides the opportunity to determine the severity of a particular surge event. The simulation determines how deep a particular surge case will be, for how long, and how many times the unit will surge during one fast stop event, providing the information needed to make a decision on whether to except the surge or not.

Method 3 also gives the opportunity to analyze how complicated systems with multiple compressors will behave and interact together. Simulations of this nature can help reduce the overall facility risk by foreseeing upset conditions as shown in the previous case, thus increasing the reliability achieved in a particular installation.

In an effort to demonstrate some complexities that can arise in the real world, a case study of a major oil and gas pipeline operator compressor station is provided. The scope of this compressor station expansion project included converting the station to accommodate reverse flow capability, addition of after gas coolers to units 6 and 7, and the addition of unit 8 with after gas cooling. As part of the addition of after gas cooling for units 6 and 7, significant piping changes were made to the suction and discharge headers to allow for a hot

and cold recycle, as discussed previously. As such, the operating company engineers grew increasingly concerned that the surge control systems for units 6 and 7 would not be adequate, given significant piping additions leading to increased volume, relocation of surge valves, and the addition of a new centrifugal compressor unit. This concern grew out of the fact that the compressor vendor typically uses a “lumped parameter” analysis method to provide recommendations for surge control design. On typical projects, lumped parameter results are provided to the EPC for final piping design and valve procurement, installation and operation.

Given the complexities of this project, the operator felt it would be prudent to utilize Method III as described herein instead of the lumped parameter method. The analysis was able to be completed without impact to the overall project schedule and was coordinated successfully with the EPC. The Method III analysis results and recommendations were issued to the operator prior to major procurement activities, which allowed for procurement of the proper surge control valves. Subsequently, valve vendor data sheets of the actual valves were rerun in the Method III analysis model to verify the accuracy of the results and recommendations.

## CONCLUDING REMARKS

The old belief that “a single combined surge/recycle line is acceptable and is commonly used in the industry in the design of compressor stations” should be re-examined vigilantly. This paper presents three methodologies to assess the adequacy of such a single combined surge/recycle system to protect the compressor from undergoing deep surge during ESD.

It is also important to recognize the influence of salient parameters that play a key role in the dynamics of the recycle systems in compressor stations for all intended purposes and functions, namely: startup, part loads, surge control, and surge protection following ESD or fast-stop. These very key parameters are:

1. Compressor/power turbine rotor inertia;
2. Compressor pressure ratio (i.e. compressor adiabatic head);
3. Volumetric capacitance of recycle system;
4. Recycle system response time (i.e. recycle valve pre-stroke delay, stroke time, time of arrival of expansion and pressure wave from the recycle valve to the compressor outlet and inlet, respectively);
5. Compressor performance characteristics; and
6. Flow capacity of the recycle system.

The designer should always consider all of the above parameters with the aid of the methodologies presented in this paper. These methodologies with the aid of dynamic

simulations should facilitate the right decision in designing an adequate recycle system for the benefit of equipment integrity, performance and safety.

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