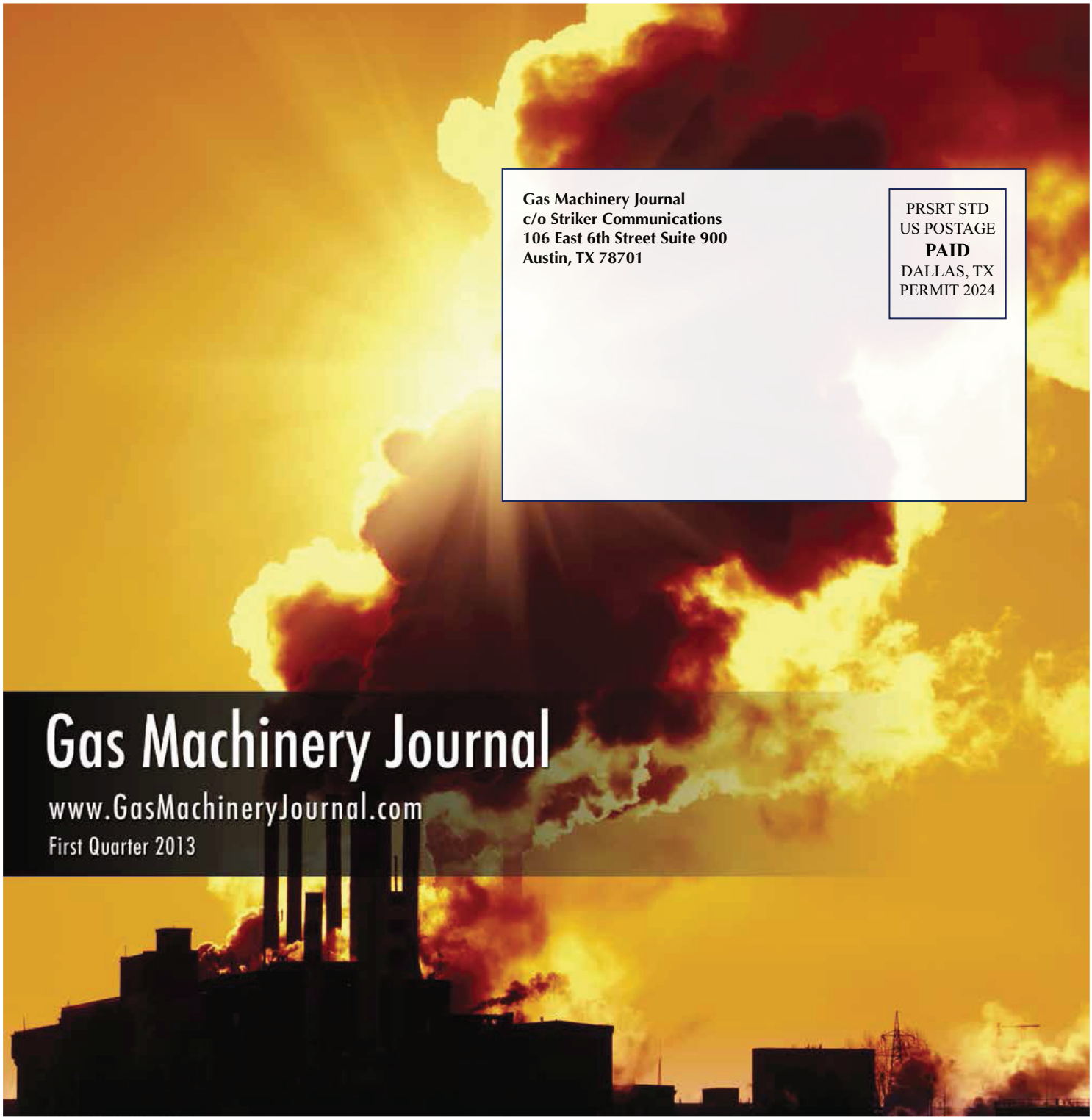


Gas Machinery Journal
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Gas Machinery Journal

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First Quarter 2013

INFLUENCE OF INLET PARAMETERS ON CENTRIFUGAL COMPRESSOR SURGE LIMIT LINE, NUMERICAL ANALYSIS

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INTRODUCTION

Actual centrifugal compressors anti-surge protection systems are based on the Surge Limit line (SSL). SSL is the description of the surge points locus and, in the current practice, it's assumed to be invariant with centrifugal compressor inlet conditions. The main purpose of this paper is to present the results of a numerical study aimed to investigate the effect of variations of centrifugal compressors inlet conditions on the Surge Limit Line.

The results presented in this paper will provide quantitative evaluation on how the Surge Line changes as consequence of variations of the gas mixture composition and thermodynamic suction conditions (temperature and pressure).

After a preliminary introduction on the actual surge protection systems and Surge Limit Line, the investigation method will be presented and results of two case studies will provided. Case studies results will show the effect of inlet conditions variation on the Surge Line at high and low operating pressures.

This paper will furthermore provide some considerations about the effect that variations of compressed gas inlet conditions may cause on actual anti surge system protection effectiveness. Actual anti-surge systems application validity range will be than discussed and relevant considerations will be supported by numerical data.

All numerical evaluations reported in this paper have been developed using most recent thermodynamic theories and machine aero mechanical models. Calculation algorithms used are able to predict both machine behavior and thermodynamic real gas properties under different operative conditions. More details on the calculation method and algorithms used will be given in the following paragraphs, and relevant document are recalled in paragraph 6.

All calculations in this study have been executed using a dedicated software tool (Cmap), developed at IPC research lab. Cmap has been designed to predict easily and quickly centrifugal compressors performance under different inlet conditions and with variable hydrocarbons gas mixtures composition.

NOTES ON COMPRESSOR SURGE AND ACTUAL ANTI SURGE PROTECTION SYSTEMS

The purpose of this paragraph is to provide a simple explanation of the compressor surge phenomenon and quickly recall how actual anti-surge systems work.

Surge is a well know instability phenomenon that consists in a rapid oscillation of the mass flow elaborated by the compressor, accompanied by a characteristic noise and high vibrations.
During the surge, the flow is suddenly reverted form the discharge to the suction. This reverse flow through the compressor causes high mechanical stresses on the machine internal components. The surge is than an abnormal operative condition, which can have a destructive nature, and could cause, when the machine remains in this condition without adequate protections, damages or failures of the compressor.

Actual protection methods have been designed with the intention to run the compressor safely far from surge points. Today the "state of the art" for anti-surge systems provides a protection action consisting in opening, partially or totally, a special control valve (anti-surge valve) located on a line that recycles the gas from the discharge to the compressor suction. In this way the control system reduces the overall line resistance and increases the elaborated flow, moving the compressor operative point to the right of the characteristic curve corresponding to the actual operative speed.

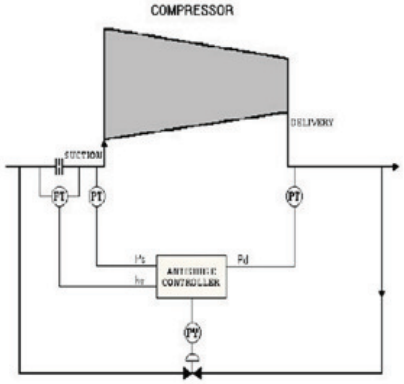
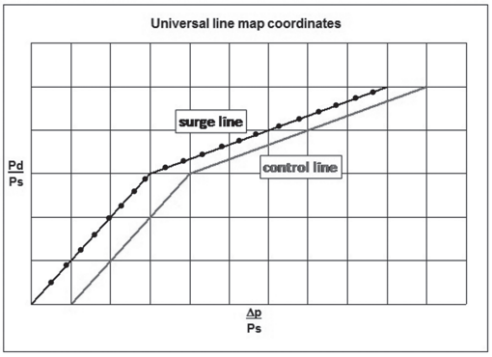


Figure 1 (above) shows a typical plant layout where there is a recirculation line that includes a re-cycle control valve (anti-surge valve).

The anti-surge valve is commanded by a dedicated PID controller, usually embedded in the protection system PLC. The Surge protection logic embeds the Surge Limit Line (SLL) and the correlated Surge Control Line (SCL).

Figure 2 (below) shows an example of Surge Limit Line. (SLL) and the Surge Control Line (SCL) that usually is calculated with a as 10% flow safety margin from the SLL.



Using field readings, the protection logic calculates the actual operative compression ratio (β) and uses the stored SCL data to determine the corresponding actual flow limit parameter. This value is then used as set point for the anti-surge valve PID controller. The process variable instead is the actual flow parameter $\frac{\Delta p}{p_1}$ also obtained from the field readings.

From the above description, it's evident how actual surge protection systems rely completely on the concept of the SLL. This is basically the central element of the actual systems protection action.

At this point, it is than important recall that the SLL concept is based on some main hypothesis. In fact the SLL is a simplified correlation between the compression ratio β and the flow parameter $\frac{\Delta p}{p_1}$ that identifies the surge points. This simplified correlation is derived applying:

a) The hydraulic affinity laws (fan laws).

$$H_p = K_1 Q^2 \quad \text{(eq.1)}$$

b) The expression of Polytrophic Head for perfect gas:

$$H_p = \frac{n}{n-1} z_1 R T_1 \left[\beta^{\frac{n-1}{n}} - 1 \right] \quad \text{(eq.2)}$$

c) The expression of the volumetric flow rate trough the suction flow meter:

$$Q = K_0 \sqrt{\frac{\Delta p}{\rho_1}} \quad \text{(eq.3)}$$

d) The real Gas state equilibrium

$$\rho_1 = \frac{p_1}{z_1 R T_1} \quad \text{(eq.4)}$$

Using the above hypothesis and introducing a simplifying approximation (conservative for the protection purposes)

$$\frac{n}{n-1}\left(\beta^{\frac{n-1}{n}} - 1 \right) \cong \beta - 1 \quad \text{(eq.5)}$$

It's possible to obtain the SLL final expression as correlation between the flow parameter $\frac{\Delta p}{p_1}$ and the compression ratio β:

$$\frac{\Delta p}{p_1} = K \times (\beta - 1) \quad \text{(eq.6)}$$

This expression of the SSL seems to be invariant with gas inlet conditions (hence it's some time called "Universal Surge Line") and being simple it gives the possibility to be easily implemented on process computers. This appeared as a great advantage in the in the early stages of anti-surge applications (the sixties), when engineers where looking for surge locus formulation very simple, to be implemented with very modest calculation capability available at that time. For this reason it has been largely used in the past and it is still today used on

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actual surge protection systems. But it has also some limitations, in fact recalling the base hypothesis it is possible to argue that

1. The $H_p - Q$ flow curve depends from gas suction condition.
2. The affinity law is valid for liquid flow, and can be considered applicable to gas for low compressibility flows i.e. low Mach flows.
3. Also when applicable the affinity law is valid in a small range around a reference point and cannot be used to describe the overall range of compressor surge point without violate the considered hypothesis applicability limits.
4. Also the eq. 5 is valid for low β, even if introduces conservative errors.

These consideration shows how finally the SSL depends on the inlet suction conditions; even this is much better evident only in compressible flows conditions. The point 1) and the Affinity laws appear to be the main hypothesis. These can be considered applicable for single stage compressors operating at low Mach numbers. For multistage compressors and for compressors running at higher Mach numbers it should be considered a surge locus different from the one obtained extending the fan law validity on all surge points; also the real surge locus will depend on the real behavior of the gas in the actual gas inlet condition i.e. inlet pressure, inlet temperature and inlet gas mix composition.

NUMERICAL INVESTIGATION CALCULATION METHOD

The purpose of the investigation is to check the effect of variation of inlet parameters on the Surge line and in particular check if the surge line remains constant or if it changes. Input data for the analysis are the compressor performance map in design conditions and the relevant inlet gas condition (gas mixture composition, inlet pressure and temperature). Based on these inputs the calculation method proceeds with the following main steps:

1. Availability of compressor design conditions performance map
2. Derivation of the Surge Line $\beta - \frac{\Delta p}{p_1}$
3. Calculation of compressor off-design performance map
4. Analytical determination of the surge points for each operative speed
5. Derivation of the numerically evaluated surge line
6. Check between the Surge Line initial (point 2) and numerically evaluated (point 5)

The detail of the calculation method is herewith described.

Step1) The starting point is the availability of compressor performance map in design condition. From this map the surge locus is derived. The equation to calculate the surge points is:

$$\frac{\partial\left(\frac{P_d}{P_s}\right)}{\partial \dot{V}} = 0 \quad (1)$$

Where

P_d = Discharge pressure

P_s = Suction pressure

$\dot{V}$ = Volume flow

Step 2) With the off design inlet conditions, the new compressor performance map is calculated. This step is developed using the Cmap software. Cmap allows developing integrated aeromechanical and thermodynamic calculation useful to predict the compressor performances in off design conditions. The software algorithm is characterized be the capability to consider the compressed gas mix as real gas. All mixture properties are than derived using the equation of state. In this analysis the Lee Kesler equation of state has been used. Among other very important are the calculation for each performance point of the gas mixture compressibility and real gas polytrophic exponents. The availability of these accurate thermodynamic properties as function of the gas mixture composition and inlet an outlet pressure and temperatures allows the software to run with higher precision the aeromechanical routines that provides final results for compressor performances. These calculation are not based on affinity law or other approximation, calculation are based on the availability of a non dimensional model of the compressor based on correlations of work coefficient, flow coefficient parameterized by the mach number. Cmap software produced output performance maps are than analyzed for finding the surge points with the criteria (1) for several operative speeds. This numerical process allows obtaining the numerically evaluated surge line. The Surge line is then calculated from compressor performance map with reference to inlet off design conditions.

The two obtained surge lines (DC and ODC) are then drawn on a plan having as x-axes the ratio between Δp across the orifice and the suction pressure (Ps) and as y-axes the compression ratio (Pd/Ps).

The error between the design and off design Universal surge lines is then calculated with reference to the compressor inlet volume flow: on equal compression ratio, it is calculated the percentage error between $\frac{\Delta p}{Ps}$ in case off design condition with respect design condition.

CASE STUDIES

Next, two real cases will be presented:

Case 1: C1 - Compressor working with low pressure suction condition

Case 2: C2 - Compressor working with high pressure suction condition

In each one of these cases two different compressors running condition have been considered:

DC (Design Condition)

ODC (Off Design Condition).

For the Off Design Condition many sub-cases have been investigated with different inlet pressures, temperature and gas mix composition.

The following cases have then been studied:

C1 - DC (Case 1, Design Condition)

C1 - ODC (Case 1, Off Design Condition)

C2 - DC (Case 2, Design Condition)

C2 - ODC (Case 2, Off Design Condition)

For both cases, this study will show how the limit surge line changes when inlet conditions move from design values to off-design values.

C1 - Case study 1: Compressor working with low pressure suction condition.

In this case study a centrifugal compressor running in different inlet conditions.

Starting from the DC condition (design condition) the surge line has been calculated changing respectively molecular weight (ODC 1 and ODC 2), pressure (ODC 3), temperature (ODC 4) and both properties (ODC 5), as shown in the following table.

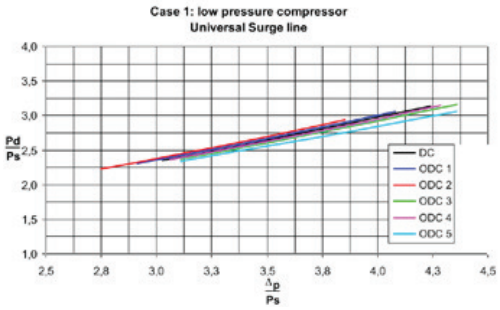
Case 1 low pressure suction condition				
Operative conditions	p1 [bar a]	T1 [°C]	M [g/mole]	GAS mix (*)
DC	67,5	38,5	16,04	Mix design
ODC 1	67,5	38,5	19,24	Mix 1
ODC 2	67,5	38,5	23,79	Mix 2
ODC 3	83,0	38,5	16,04	Mix Design
ODC 4	67,5	23,0	16,04	Mix Design
ODC 5	83,0	23,0	23,79	Mix 2

(*) Gas mix has been obtained modifying the gas mix design composition. Calculations have been developed using the complete gas mix composition. Gas mixes used are available after the bibliography.

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Influence of Inlet Parameters on Centrifugal Compressor Surge Limit Line, Numerical Analysis, cont'd

The following picture shown the surge limit lines obtained with



different inlet conditions:
The following table compares the design conditions (DC) versus

Case 1 low pressure suction condition					
Comparison	Δp %	ΔT [°C]	ΔM %	Pd/Ps	error %
DC - ODC 1	0	0	+20	2,5-3,5	- 1,1
DC - ODC 2	0	0	+48	2,5-3,5	- 2,6
DC - ODC 3	23	0	0	2,5-3,5	+1,7
DC - ODC 4	0	-15,5	0	2,5-3,5	+0,9
DC - ODC 5	23	-15,5	+48	2,5	+4,0
				3,5	+7,0

the off design conditions (ODC),

In the previous table it can be noted that for the off design conditions considered (obtained varying separately the pressure, temperature or the molecular weight); the maximum error calculated is 2.6 %. If the variation on the inlet conditions is applied simultaneous on pressure, temperature and mix, the maximum error calculated is 7%. (with compression ratio of the 3.5).

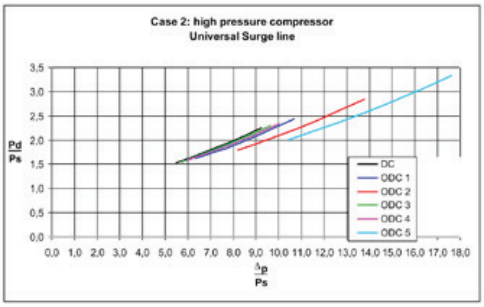
C2 - Case study 2: Compressor working with high pressure suction condition.
As in C1, in this case study a centrifugal compressor running in different inlet conditions.

Case 2 high pressure suction condition				
Operative conditions	p1 [bar a]	T1 [°C]	M [g/mole]	GAS mix (*)
DC	267,5	60	16,04	Mix design
ODC 1	267,5	60	19,24	Mix 1
ODC 2	267,5	60	23,79	Mix 2
ODC 3	285,0	60	16,04	Mix Design
ODC 4	267,5	45	16,04	Mix Design
ODC 5	285,0	45	23,79	Mix 2

Starting from the DC condition (design condition) the surge line has been calculated changing respectively molecular weight (ODC 1 and ODC 2), pressure (ODC 3), temperature (ODC 4) and both properties (ODC 5), as shown in the following table:

(*) Gas mix has been obtained modifying the gas mix design composition. Calculations have been developed using the complete gas mix composition. Gas mixes used are available after the bilbiography.

The following picture shown the surge limit lines obtained with different inlet conditions:



The following table compares the design conditions (DC) versus the off design conditions, (ODC):

Case 2 high pressure suction condition					
comparison	Δp %	ΔT [°C]	ΔM %	Pd/Ps	error %
DC - ODC 1	0	0	+20	1,5	5,5
				2.7	6,8
DC - ODC 2	0	0	+48	1,5	16,2
				2.7	18.6
DC - ODC 3	+6,5	0	0	1,5	1,5
				2.7	2,1
DC - ODC 4	0	-15	0	1,5	3,4
				2.7	4,1
DC - ODC 5	+6,5	-15	+48	1,5	27,6
				2.7	31.2

In the previous table it can be noted that for the off design conditions considered (obtained varying separately the pressure, temperature or the molecular weight); the maximum error calculated is 18.6 %. If the variation on the inlet conditions is applied simultaneous on pressure, temperature and mix, the maximum error calculated is 31.2%. (with compression ratio of the 2.7). It is interesting to note that the correct surge flow line moves to right with respect to the initial (design) surge line. This fact implies that the control system is underestimating the surge flow, and then the compressor could be potentially exposed to surge events

CONCLUSIONS

The analysis developed indicates that in a low pressure compressor if the inlet conditions change it hasn't problem of the surge but a reduction of the operating efficiency.

Instead in a high pressure compressor it varying the inlet condition the errors calculated (more 30 %) are greater than safety margin (usually 10 %).

Analysis proposed and described in this paper can allow affirming that the actual centrifugal compressors protection systems based on simplified hypothesis such as the ideal gas law, validity of hydraulic affinity laws are valid only in a certain range of application. For a high pressure compressor it varying the inlet condition the errors calculated are greater than safety margin. Consequently the protection become inefficient and potentially can cause the damaging of the compressor.

The software developed by IPC allows predict the performances of a centrifugal compressor under varying thermodynamic conditions of the inlet gas. The prediction of compressor performances is accurate even at high pressures, where the ideal gas theory commonly used introduces considerable errors and implements advanced protection from surge, overcoming limits of the current technology.

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Gas composition of the gas mixes used:

Mix Design:

Symbol	% mol
Methane	100
Total	100
M (g/mole)	16.04

Mix 1:

Symbol	% mol
Nitrogen	1.46
Methane	80.51
Ethane	14.69
Propane	3.19
i-butane	0.07
n-butane	0.08
Total	100
M (g/mole)	19.24

Mix 2:

Symbol	% mol
Nitrogen	0.08
Carbon Dioxide	3.62
Methane	73.11
Ethane	10.44
Propane	6.5
i-butane	0.83
n-butane	1.82
i-pentane	0.46
n-pentane	0.5
n-Hexanes	0.74
n-Heptane	1.04
Hydrogen Sulphide	0.57
n-Octanes	0.25
n-Nonanes	0.04
Total	100
M (g/mole)	23.79