THE WAY THE VENTURI AND ORIFICES WORK
CHAPTER 2

All industrial combustion systems are made up of 3 main parts:
1) The mixer which mixes fuel gas with combustion air in the correct ratio and sends the mixture to the burner at some fixed pressure.
2) The burner, where the combustion reaction starts.
3) The controlling and safety devices and any other manual or automatic component designed to regulate the quantity of fuel and comburent flowing to the burner.

WORKING PRINCIPLES OF AN ORIFICE

The dimension and shape of a mixer rely on the main principles controlling the passage of a fluid through an orifice.
An orifice is an opening or hole in a surface causing a pressure drop when a fluid passes through it. This is a somewhat rough definition which though is rather helpful to understand some phenomena relating to the dynamics of fluids.
The formula governing the flow of some gaseous fuel through an orifice, at pressures of up to 3,500 mm H_2O is:

$$Q = K \cdot S \sqrt{\frac{2g \cdot h}{p}} \qquad \text{Eqn. 01}$$

where
- Q = outflow or orifice capacity (m^3/s)
- K = coefficient of discharge or orifice efficiency
- S = area of the orifice (m^2)
- g = acceleration of gravity (~9,81 m/s^2)
- h = pressure drop through the orifice (mm H_2O)
- p = gas specific weight (kg/m^3)

The pressure drop through an orifice results from the difference between P_1 and P_3 (see Fig. 1).
The coefficient of discharge of an orifice accounts for its efficiency as compared to the efficiency of an ideal hence frictionless orifice.
Such value ranges from 0.4 to 1.3 depending on the shape and angle of flare of the outer face of the orifice.
Well-designed orifices and nozzles for atmospheric burners have a coefficient of discharge ranging from 0.8 to 0.85.
The amount of gas flowing through an orifice depends on the area of the orifice, the pressure drop through the orifice, that is the difference between P_1 and P_3, as well as the specific weight of gas.
Obviously when the gas flows through nozzle, P_3 will always be lower than P_1. The pressure referred to as P_2 is the pressure corresponding

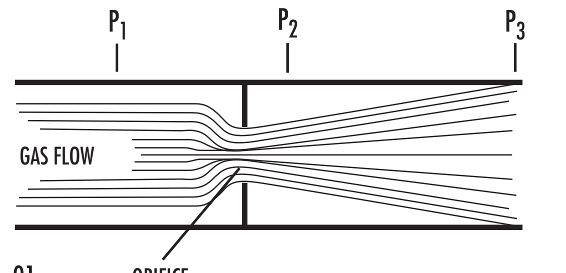

Fig. 01

to the maximum restriction the gas encounters on its way through the orifice. P_2 will always be lower than P_1 and P_3.
Other important relations depend on the equation relating to the orifices:

$$\frac{Q_1}{Q_2} = \sqrt{\frac{\Delta P_1}{\Delta P_2}} \qquad \text{Eqn. 02}$$

The capacity of a fluid through an orifice of a fixed specific dimension varies when the square root of the pressure drop varies. This means for instance that a decrease from 625 mm to 25 mm H_2O of pressure P_1 of the fluid upstream of the orifice will entail a decrease in the capacity from 5 to 1.
A capacity ratio or thermal potential of a burner from 10 to 1 needs a variation in pressure from 100 to 1. One of the most important reasons why it is sometimes difficult to obtain a great capacity ratio in a burner can be explained by this relation, which shows that in order to obtain a small capacity ratio, a great pressure ratio is necessary.

$$\frac{Q_1}{Q_2} = \frac{A_1}{A_2} \qquad \text{Eqn. 03}$$

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The capacity of an orifice, at a constant pressure drop, is directly proportional to the area of the orifice itself.
By keeping pressure P1 of gas constant and doubling the area of the orifice, a double capacity is obtained as compared to the original one. More important changes in the thermal capacity of a burner may be obtained more easily by changing the area of the orifice than by changing the pressure drop through it. Yet, this entails great mechanical problems.

$$\frac{Q_1}{Q_2} = \sqrt{\frac{d_2}{d_1}} \qquad \text{Eqn. 04}$$

If the area of the orifice and the pressure drop through the orifice are kept constant, a variation in the capacity of the orifice may be obtained by changing the density of the gas.
The capacity varies in a way which is indirectly proportional to the square root of the variation in density. An orifice featuring a capacity of 2.8 m^3 of natural gas will only bear 1.8 m^3/h of propane, if the pressure drop through the orifice is left unchanged.
The tables out of which you can choos the most adequate area of the orifice, depending on the pressure drop and desired capacity, rely on a coefficient of discharge K = 0.85. The same tables refer to a gas whose density amounts to 0.56. Usually some correction factors are supplied for gases featuring a different density. When 2 out of the 3 variables relating to the capacity of an orifice are known, finding out the third dimension from the tables of the capacity of the orifice is easy and quickly done.

AIR-GAS RATIO

One of the main criterion governing the dimensioning of industrial combustion systems is that it is necessary to keep a constant ratio of air volumes to gas volumes in the mixture at the mixer outlet at any mixture load.
The air-gas ratio is usually expressed as the percentage of the theoretical air required to burn all the gas.
A 100% mixture of natural gas and air contains some 10 m^3 of air per m^3 of gas. Similarly a 100% mixture of propane and air contains 25 m^3 of air per m^3 of propane.
All mixers designed for industrial combustion systems are manufactured so as to keep the air-gas ratio constant through the whole flowfield.
A combustion system designed to operate with 80% aeration in the high-fire position, will keep the same aeration even when its capacity is decreased to the low- fire position. If the combustion system is not capable of keeping the volumetric air-gas ratio constant through the whole flowfield, the capacity will change and the features of the flame will change accordingly. Such event must absolutely be avoided except for very rare situations.

CALIBRATED FLANGES FOR FLOW REGULATION

As the capacity of an orifice depends on the pressure drop through the orifice itself, it is easy to understand that by regulating pressure P_1 (see Fig. 1) the capacity of the orifice can also be regulated.
All combustion systems which work satisfactorily possess at least 3 orifices and in particular: one to regulate the air flow; one to regulate the gas flow and one to regulate the air-gas mixing.
Fig. 2 shows 2 separated orifices, each one having a different capacity and a different pressure drop (or ΔP). The connection between the 2 orifices is simplified so as to make it is easier to understand how mixers work.
The area of the 2 orifices is calculated so as to obtain the capacity and pressure drop mentioned above. The connection between the 2 orifices is designed to connect the pressure drop of the gas orifice (ΔP_2) to the pressure drop of the air orifice (ΔP_1) so that any pressure variation in the first one corresponds to a proportional pressure variation in the other one.

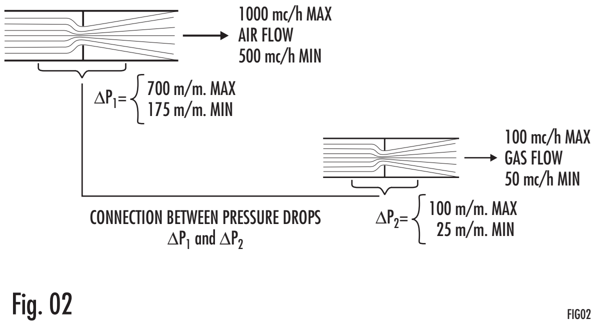

Fig. 02

A decrease in the pressure drop (ΔP_1) from 700 mm H_2O to 175 mm H_2O (that is a decrease in pressure from 4 to 1) will entail a 50% variation in the air capacity. The connection between the 2 orifices

causes the pressure drop through the gas orifice (ΔP_2) to change accordingly from 100 mm to 25 mm H_2O. This entails a 50% decrease in the gas capacity. The range of variation through which the connection between the 2 orifices manages to keep this ratio constant determines the load limits of the mixing system which is called "proportional". If the system is correctly dimensioned, the ratio of the maximum capacities to the minimum ones may exceed 20/1.
Thanks to this connection between one orifice and the other it is possible to keep the air-gas ratio constant through the whole potential flowfield of the combustion system. This connection is easily reversible so as to obtain the same result by regulating the gas pressure and hence the air pressure.

Industrial air-gas mixers rely on this principle that is 2 orifices connected one to the other to always keep the air-gas ratio constant.
It is clear that a combustion system may be designed to change, via the same mechanism of connection, the area of the 2 orifices keeping the pressure drops through the orifices constant. With this system exactly the same results as the ones described above may be obtained in compliance with Equation 03.
Many industrial systems designed to mix air with gas rely on this principle, though it is worth highlighting the fact that it is easier to regulate the pressure drop through the orifices than to change the areas of the orifices themselves.

WORKING PRINCIPLES OF THE VENTURI

The need for a perfect connection between 2 orifices (as described above) is at the basis of the calculation for air-gas mixers. This connection is fixed but for semplicity we have chosen to show it as if it was a mobile part of the mixer. In reality it is integrated in the mixer and placed inside it.
The gas flow through the orifice in Fig. 1 is indicated in an approximate way by the thin lines. To reduce the turbulence where the gas approaches the orifice and where it leaves the orifice, the inner shape of the orifice is studied and designed so as to follow the same pathway of the fluid passing through it. This allows to obtain very good working conditions.
The working principle of the venturi is valid both for natural draught combustion systems, where gas passes through the orifice in A (fig. 4), entraining air, and forced draught combustion systems where high-pressure air flows through the orifice entraining gas. The working principle of the venturi can be explained more easily when considering the main pressures at stake: P_1, P_2, P_3, (fig. 3).

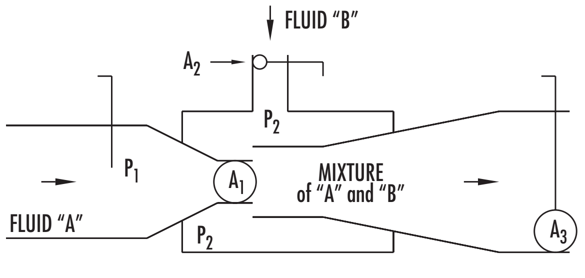

Fig. 03

FIG03

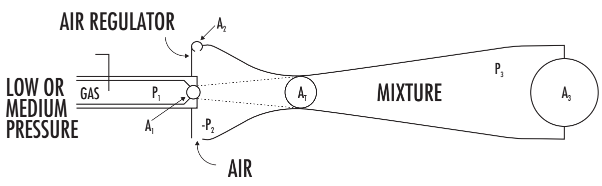

Fig. 04

FIG04

As we have already said, when gas passes through orifice A_1 a pressure drop occurs through the orifice itself, hence P_1 exceeds P_3, whereas P_2 is always lower than P_1 and P_3. The value of P_2 is determined by the shape of the venturi and the value of the pressure drop from P_1 to P_3. Standard air-gas mixers relying on this principle are calculated so as to always obtain a negative P_2, whose value is lower than the atmospheric pressure. The working of the venturi is governed by the variations in the 3 pressure values.

ATTENTION: the valve shown in Fig. 3 on the gas mixture pipe has a merely educational goal. In practice it is never used and it is usually not recommanded or even clearly prohibited.

Let's assume to keep area A_3 fixed and the inlet valve open in the "fluid A" position, the maximum capacity will be through orifice A_1 as well as a specific value of pressure P_3 and draft P_2.

Table 1

P_1 mm H_2O	P_2 mm H_2O	P_3 mm H_2O
+ 700	- 100	+ 250
+ 350	- 50	+ 125
+ 175	- 25	+ 62,5
+ 87,5	- 12,5	+ 31,25

Table 1 shows the variations of the 3 pressures when the valve on the pipe for the intake of "fluid A" is operated. The variation in pressure P_2 and P_3 is directly proportional to the variation in pressure P_1.
By calibrating the inlet pressure of "fluid B" through orifice A_2, that is by fixing it at the atmospheric pressure value, the pressure drop through orifice A_2 will correspond to the draft in P_2. In Table 1, the pressure drop through A_2, corresponding to pressure P_1 of 700 mm H_2O amounts to 100 mm H_2O. Therefore the pressure drops through orifice A_1 and A_2 will be directly proportional one to the other with a variation only in pressure P_1.

Table 2

P_1 mm H_2O	ΔP through A_1 mm H_2O	ΔP through A_2 mm H_2O	Capacity of fluid A Nm^3/h	Capacity of fluid B Nm^3/h
700	800	100	1000	100
350	400	50	710	71
175	200	25	500	50

Table 2 shows how the 2 pressure drops change when pressure P_1 changes.
As the pressure drops through the 2 orifices are directly proportional, according to equation 2, also the capacities through the orifices will be proportional one to the other. The last 2 right-hand columns of Table 2 show that when the pressures vary, the capacity ratio between the 2 fluids stays constant (from 10 to 1) through the whole range of pressure variations. The connection described above in figure 2, here is clearly highlighted. In practice this connection is the result of the inner shape and mechanical precision in the mixer manufacturing, as well as of the correct location of orifices A_1 and A_2 .
In practice, the pressure of "fluid B" at the inlet of orifice A_2 may be maintained at the value of the atmospheric pressure in two different ways:

a) in natural draught burners (the air being entrained from the atmosphere is at atmospheric pressure);
b) in forced draught burners where a zero governor is used to reduce the pressure of the exhaust gas to zero.

A study of the pressure unbalance which may occur in the mixer in P_1, P_2 and P_3 can explain the working principle of the venturi better.
A variation in pressure P_3 may be obtained by changing the area of A_3 and keeping pressure P_1 and the areas of A_1 and A_2 constant. Any variation in pressure P_3 which is not the result of a variation in pressure P_1 will modify the pressure drop between P_1 and P_3. As we have already said, it is the value of such pressure drop which determines draft P_2.
By decreasing the pressure drop (that is the pressure difference) between P_1 and P_3, the negative pressure will decrease accordingly and viceversa by increasing the pressure drop between P_1 and P_3 the value of negative pressure P_2 will also increase.
Table 3 shows how pressures P_2 and P_3 vary when the valve is slowly closed until it reaches the P_3 position so as to reduce the free area of A_3.
The pressure variations mentioned above are not exactly as the ones which may be obtained in practice in a mixing system, but are a useful reference.
The importance of Table 3 lies in the fact that it shows the trend of the pressure variations causing some undesirable effect on the mixing system. As you can see the variations in pressures P_2, resulting from the variations in pressures P_3 are not proportional to the variations in P_3.
When pressure P_3 increases above the critical point, pressure P_2 becomes positive. In these conditions the gas flowing out of orifice A_1 will also flow out of orifice A_2.
In pre-mix or forced draught combustion systems where the fluid flowing through A_1 is air, the latter instead of entraining the gas through orifice A_2, will flow out of the same orifice to go into the atmospheric regulator, upstream.
Given that atmospheric regulators are designed to allow for the passage of the flow in one direction only, such anomalies in standard working will cause the atmospheric regulator to close hence the flow of combustion air to the mixing system will be interrupted. For the same reasons the gas flow will also be interrupted.

Table 3

P_1 mm H_2O	P_2 mm H_2O	P_3 mm H_2O	Area of A_3
+ 700	- 100	+ 250	Decreasing ↓
+ 700	- 75	+ 280	
+ 700	- 25	+ 300	
+ 700	- 12,5	+ 350	
+ 700	+ 12,5	+ 380	

When valve A_3 is gradually opened, pressure P_3 will decrease and the negative value of pressure P_2 will increase. This is shown in Table 4.
In this case too the values relating to the pressure variations are merely explanatory, the main phenomenon being the trend of the variations of these pressures.
Similar variations may be registered on a venturi system by changing area A_1. By increasing area A_1 and keeping the conditions of pressure of "fluid A" in P_1 and the atmospheric pressure at the inlet of "fluid B" constant, as well as leaving area A_3 unchanged, pressure P_3 will automatically increase.
This variation is caused by the increase in the fluid capacity passing through constant area A_3. Any variation in pressure P_3 entails an immediate variation in draft P_2.
If area A_1 is increased beyond a fixed levels and hence P_3 exceeds the fixed levels too, pressure P_2 becomes positive. These are exactly the same conditions we would have obtained if area A_3 had been decreased and area A_1 had been kept constant. Similarly by reducing area A_1 below the original value, pressure P_3 will also decrease and the negative value of pressure P_2 will automatically increase.
In practice ideal conditions of negative pressure P_2, corresponding to the maximum pressure P_3 which can be obtained and to a fixed area A_3, may be obtained with only one fixed area of orifice A_1.
When operating at pressures of P_3 close to maximum levels, with a minimum of negative pressure P_2 some problems may be encountered, like a slight change in area A_3 for instance, due to fouling, would modify the capacity of orifice A_2 with a subsequent change in the air-gas ratio.
For air low-pressure mixers, manufacturers fix the maximum working pressure of mixture P_3 for a fixed boost P_1. These maximum pressures of P_3 which are recommanded by manufacturers are the result of the experience of many years and, in order to obtain satisfactory draft conditions P_2 , it is better never to exceed them. Atmospheric or natural draught mixers are always designed to supply a specific free area to the burners (equal to area A_3) and are usually sold as a whole. This type of burners are equipped with plates, rings, drilled pipe and single torch. The free area of the burners is predetermined so as to obtain ideal working conditions.

Table 4

P_1 mm H_2O	P_2 mm H_2O	P_3 mm H_2O	Area of A_3
+ 700	- 100	+ 250	Increasing ↓
+ 700	- 150	+ 200	
+ 700	- 250	+ 100	