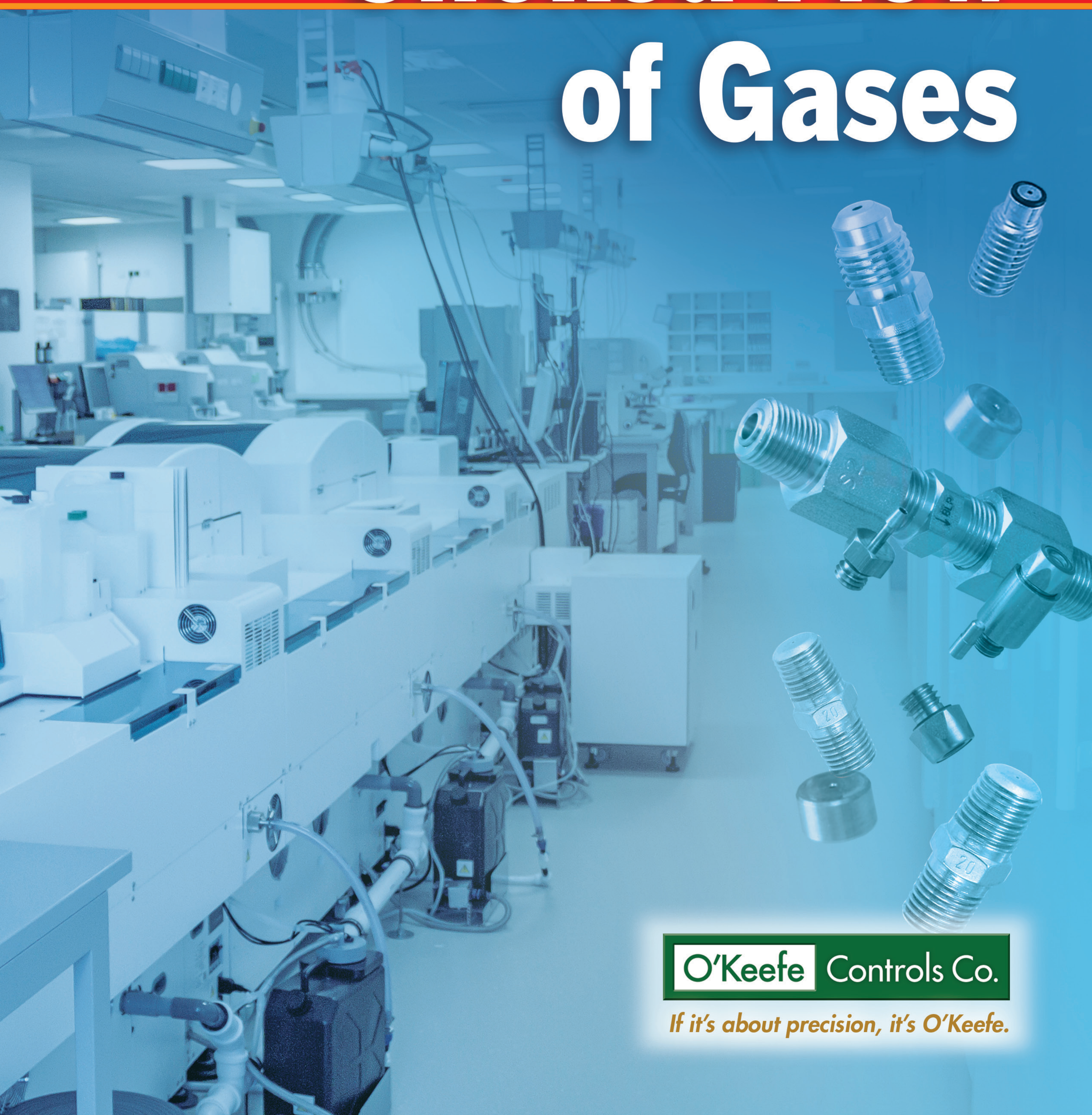
Understanding Choked Flow of Gases



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Understanding Choked Flow of Gases

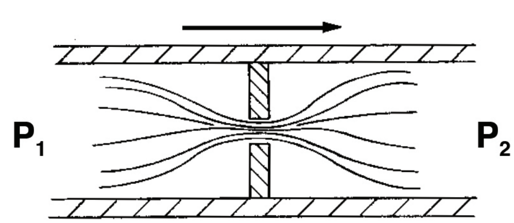
In applications such as the mixing of specific gas volumes, ***precision*** *is required in gas flow in order to achieve extremely accurate results, time after time. It is critical to understand the science behind gas flow — the various factors that are involved in achieving precise control — and to be able to use that information to determine the correct orifice size that will create desired results.*

The phenomenon of "Choked Flow" or "Critical Flow" is an essential part of understanding the way gas flows through an orifice.

What is Choked Flow?

When a gas is flowing through an orifice, the gas velocity in the orifice is a function of the inlet and outlet pressures. When an orifice is exposed to equal inlet and outlet pressures a no flow or zero velocity condition in the orifice occurs. If the outlet pressure is lower than the inlet pressure by a small amount, we begin to see a flow of gas and a gas velocity in the orifice occurs. This lower pressure condition is communicated upstream at the speed of sound in the gas.

As the outlet pressure continues to lower, perhaps by a valve opening downstream, the gas velocity in the orifice continues to increase. If the outlet pressure continues to decrease, the velocity of the gas in the orifice will reach the speed of sound or ***sonic velocity.*** This occurs for air flow when the absolute pressure ratio is .528, i.e., when the downstream absolute pressure is 52.8% of the upstream absolute pressure or less. In simple orifices, upon reaching sonic velocity, the gas cannot accelerate any further — the gas has reached a *maximum* velocity. In other words, for a fixed inlet pressure and an outlet pressure that produces sonic velocity in the orifice, a limit is achieved that cannot be exceeded.

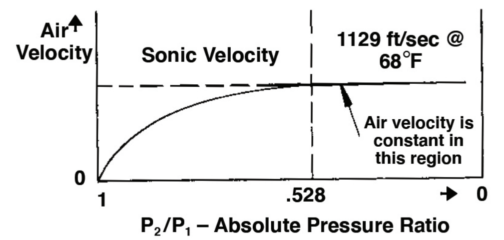


Sonic velocity occurs for air flow when $P_2 / P_1 \leq .528$.

The phrases, “Choked Flow” or “Critical Flow” have been coined to describe this condition of sonic velocity in the orifice. A more accurate term might be “Choked Velocity” rather than “Choked Flow” because the parameter that is “choked” or “limited” is the *velocity* of the gas.

Choked flow is demonstrated in the diagram opposite. As the pressure P_2 drops, more gas will flow. The drop in P_2 is communicated upstream at the speed of sound. The velocity in the orifice increases. P_1 is held constant in this example. The velocity in the orifice continues to increase as the pressure differential increases.

Once the velocity in the orifice reaches sonic velocity, no further decrease in P_2 is communicated upstream. In this case the velocity is limited, and with a constant P_1 the flow rate of gas is also limited.



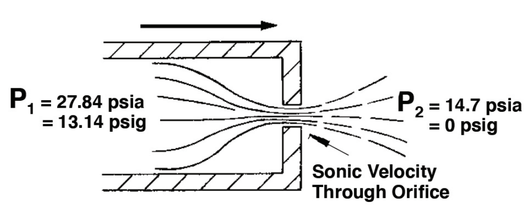
The air flow velocity is limited once the absolute pressure ratio is ≤ .528.

A Common Misconception

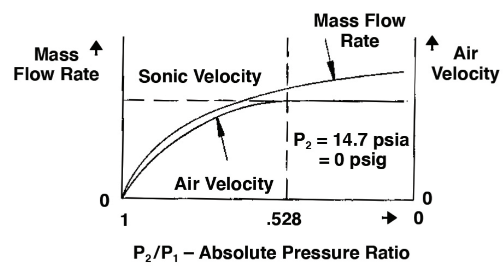
In a choked flow condition, a common misconception is to assume that the limited velocity also causes limited *mass* flow, however this is not the case.

Mass flow rate is the amount of a gas that passes through an orifice per unit of time. The three primary parameters that effect the mass flow rate through an orifice are velocity, density, and orifice area. Other factors including gas temperature and orifice entry and orifice exit conditions have an effect, but let us disregard them for now. We've learned that when gas moving through an orifice reaches sonic velocity, a decrease in downstream pressure does not cause an increase in velocity through the orifice. However, mass flow rate being a function of density, any upstream air pressure increase will cause the *density* of the air to increase linearly with the inlet pressure increase, allowing a greater mass of air to flow through, although its sonic orifice velocity remains constant.

In the example illustrated below, when P_2 is 14.7 psia and P_1 is 27.84 psia, sonic velocity occurs through the orifice. Once this happens, as P_1 is increased there is no further increase in the *velocity* of the air flowing through the orifice. However, the air *density* will increase, causing a greater *mass flow rate*.



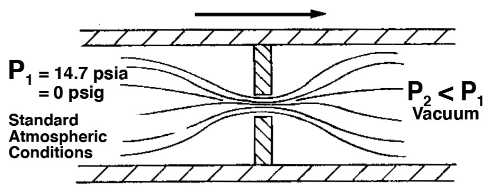
Conditions for the onset of sonic velocity in air flow.



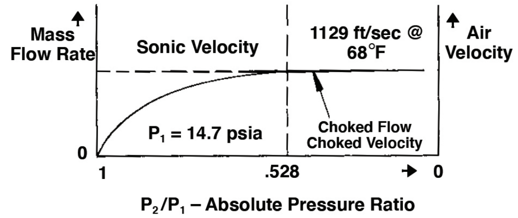
Even though the air velocity through the orifice is limited to the speed of sound, the mass flow rate continues to increase as the absolute pressure (P_1) increases.

Vacuum Conditions

It is easiest to observe choked flow when the inlet pressure is atmospheric, or the same pressure conditions in the room around you, and the outlet pressure is lower than atmospheric — a vacuum condition. In this specific condition, both air velocity and mass flow rate become choked when sonic velocity is reached through an orifice. The condition of fixed inlet density *and* velocity causes the mass flow rate limitation.



Air at atmospheric pressure enters the orifice and flows to a downstream vacuum pump.



For atmospheric inlet pressure and downstream vacuum, both air velocity and mass flow rate are limited.

Positive Pressure Conditions

As in the case of the above vacuum conditions, there are many situations in which choked flow does occur for positive (above atmospheric) pressure. Maintaining a *fixed* inlet pressure to the orifice while allowing the outlet pressure (back pressure) to vary causes a range of outlet pressures over which the mass flow rate is fixed. (See chart opposite.) For example, with an inlet pressure of 80 psig, the mass flow rate is choked (limited) and remains constant for all outlet pressures less than 35.30 psig to as low as a complete vacuum.

Understanding and utilizing these factors, along with temperature, mass flow rate can be calculated with accuracy for precise orifice sizes. Thus, precision orifices become the crucial component for numerous industrial applications which depend upon exact mass flow rates to achieve the desired results.

Sonic Velocity Conditions – Air Flow

Inlet Pressure		Outlet Pressure For Sonic Velocity	
Gage Pressure psig	Absolute Pressure psia	Absolute Pressure psia	Gage Pressure psig
100	114.7	≤ 60.56	≤ 45.86
90	104.7	≤ 55.28	≤ 40.58
80	94.7	≤ 50.00	≤ 35.30
70	84.7	≤ 44.72	≤ 30.02
60	74.7	≤ 39.44	≤ 24.74
50	64.7	≤ 34.16	≤ 19.46
40	54.7	≤ 28.88	≤ 14.18
30	44.7	≤ 23.60	≤ 8.90
20	34.7	≤ 18.32	≤ 3.62
15	29.7	≤ 15.68	≤ .98
14.7	29.4	≤ 15.52	≤ .82
10	24.7	≤ 13.08	≤ -1.62
5	19.7	≤ 10.40	≤ -4.30
1	15.7	≤ 8.29	≤ -6.47
0	14.7	≤ 7.76	≤ -6.94

Temperature 68° F

Industrial Applications

The various physical principles covered herein allows us to control the flow of gases with repeatability and accuracy via orifices manufactured specifically for extreme precision. In industrial applications where exact amounts of gases are required, we can measure this by determining the exact mass flow rate into a vessel. Let's look at some common examples.

Air Quality Applications

In air sampling for atmospheric pollutants, the use of precision orifices to control air flow into the testing canister is critical. A vacuum is drawn in a collection canister, which has a precision orifice at its inlet. Due to the pressure differential, when opened, atmospheric air is drawn in through the orifice. The extremely precise size and specifications of the orifice allow the tester to know the exact mass flow rate, and thus the exact volume of air that has been collected. This makes possible precise measurements of various gas molecules present in the sample.

Health & Safety Applications

In a lab setting where gases other than air are piped in, precision orifices are utilized to help keep the lab in accordance with safety standards and regulations. Utilizing a precision orifice in the flow line on the high-pressure side limits flow due to a pipe or regulator malfunction. This limited flow prevents dangerous atmospheric contamination in the lab. This critical flow control will ensure the gas can only reach some acceptable predetermined maximum flow rate. This provides lab workers with a survivable condition in case of an equipment failure.

Industrial Gas Mixing Applications

A correct proportion of mixed gases is necessary in various industrial products and processes. Choked flow orifices establish the proper ratio of the mixing gases. Gas flows controlled by precision orifices dictate the exact volume of each gas creating an accurate mix.

O'Keefe Controls Co.— A Global Leader in Flow Controls

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