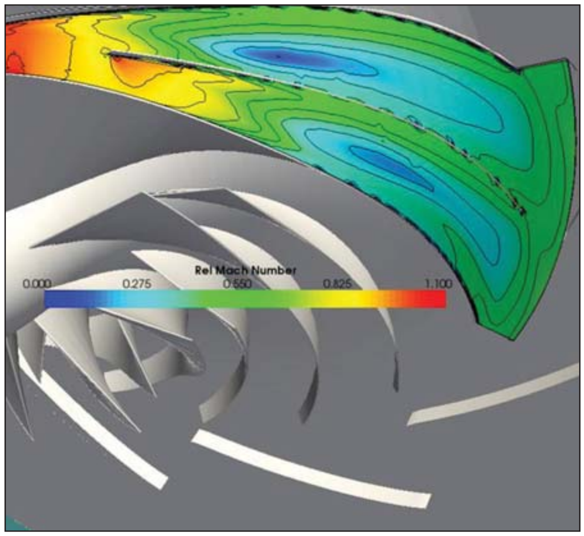
THE UBIQUITOUS COMPRESSOR: THE IMPELLER

The impeller is the key component of the compressor stage, even though expert attention must be given to all elements to derive a quality stage; but only the impeller imparts work to the flow, and hence, the total pressure of the fluid (and the total temperature) can only increase in the impeller. Several key considerations enter into the definition of a good impeller: Stage pressure ratio, specific speed, Mach number, range, head rise to surge, and life. Let's consider each of these.



Impeller plus diffuser section with CFD results

Pressure ratio (exit pressure divided by inlet pressure) of a stage (or just the overall pressure rise) sets the number and type of stages to be used; a high pressure ratio design requires multiple stages. The amount of pressure rise per stage is easily seen by using the efficiency relationship with the Euler equation for work:

$$pr = (1 + \eta U_2 C_{\theta 2}/C_p T_{00})^{k/(k-1)} \text{ or}$$
$$= (1 + (k-1)\,\eta U_2 C_{\theta 2}/kRT_{00})^{k/(k-1)}$$

for an ideal gas.

Stress limits on wheel speed, U_2, will clearly limit the pressure rise per stage, as will the molecular weight of the gas due to the gas constants k and R; refrigerants, for example, have more limited pressure rise per stage than air, for example. Usually, a number of impellers are required to meet an overall pressure rise or ratio. These stages may be on just one shaft or on multiple shafts, depending on the type of machine desired (e.g., barrel versus gear-driven). Hence, the decision of impeller number and type involves not only gas dynamics and impeller stress limits, but also rotordynamics including the choice of bearings and seals.

The specific speed is also a paramount parameter: It is defined as $N_s = N\, Q^{1/2}/h^{3/4}$, where N is the rotational speed (rpm), Q is the inlet volumetric flow, and h is the isentropic head rise for the stage. The latter is driven by the pressure rise of the stage.

Low specific speed stages are friction-dominated with generally low levels of Mach number relative to the impeller blades; simple blade forms are often used. High specific speed stages are kinetic energy-driven (frequently higher Mach numbers), wherein careful attention to blade shape is necessary to avoid unwarranted losses; friction, by comparison, has a lesser effect on performance. Barrel compressors tend to use lower specific speed stages and locate several of them on a single shaft, with careful limits on allowable Mach numbers.

Gear-driven compressors and chillers have greater control over the speed of each stage, the inlet to each stage, and often greater length per stage. Therefore, they often use somewhat higher specific speed impellers with higher limits on Mach numbers being acceptable. Turbochargers often permit some flexibility of speed choice, but space constraint may push up the specific speed.

So what is the Mach number? It is the ratio between actual speed and the speed of sound. Several different values are used in compressor evaluation. The machine Mach number is the ratio U_2/a_0. This is the impeller exit peripheral speed divided by the inlet speed of sound, and it can be found in the pr equation from above, if we expand it a bit: $pr = (1 + (k-1)\,\eta \mu M^2_{U2})^{k/(k-1)}$, where μ is the work input coefficient $C_{\theta 2}/U_2$. Here we can see that the machine Mach number drives the pressure ratio for the stage, and industry norms usually set practical limits on this number for reasons of stress (life) and performance. The machine Mach number is not a physical parameter, but rather an overall bulk characteristic. The absolute Mach number is given by C/a_0 (at any point in the flow field), and the relative Mach number is W/a_0, wherein C is any absolute velocity, and W is any relative velocity (relative to the rotating impeller).

When a value of 1 is reached for these physical Mach numbers, local sonic velocity is achieved, and above this level, the flow is supersonic, which is allowable in compressor stages, if carefully designed for. Shock waves generally occur when supersonic flow is returned to subsonic conditions. Normally, barrel compressors have subsonic flow, with limited spots of low supersonic flow at most; gear-driven compressors may realize higher Mach numbers, and transonic flow is unavoidable in refrigeration and turbocharger and gas turbine compressors.

Stable operating range, which is defined as the flow turndown from a preferred operating point to the stability limit (surge), is always of interest to the compressor designer. Industrial machines often need a lot of stability margin, and this requires design attention to many details: Controlled incidence, careful loading control, passage width restraint, and sometimes variable geometry. Wide range often requires some compromise in the peak efficiency obtained. A related performance matter is the head rise to surge, which many system specialists desire to prescribe, in order to ensure safe, stable system operation.

The problem is, however, that there is only one sensible and practical compressor design variable that allows control over this factor, and that is the impeller back lean angle or backsweep angle. One may wish for more choice, but that is the hard fact of compressor physics. If more head rise to surge is needed than afforded by the sensible choice of the backsweep angle, then the user had better be ready to accept some strong compromises to force such desires; fortunately, reason almost always prevails, and sensible numbers are invariably selected, but not without some conferring of experts!

Finally, component life must be considered in designing a centrifugal compressor impeller, and this has been made clear in the preceding paragraphs. The wheel speed U_2 sets impeller steady stress limits, as well as the stage pressure ratio; the number of stages sets the shaft length for a barrel compressor, and this requires careful rotordynamic design and excellent bearings. And the list goes on; the stress analyst and the aerodynamicist always work hand-in-hand to effect a modern impeller design. TI

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