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Parameters for evaluating the efficiency of inlet compression

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Abstract The efficiency parameters are studied in this paper for evaluating the compression quality of the inlets with different compression degrees and assessing different design methods. Self-consistency is proposed for the efficiency parameters, based on two mathematically derived efficiency parameters, entropy rise coefficient and compression quality efficiency. Two efficiency parameters are then examined for equal intensity shocks system to show their capabilities in characterizing the quality of compression system with different compression degrees, and representing the average compression efficiency of the entire inlet. And the process efficiency and compression quality efficiency are compared in the Mollier diagram to afford a clear understanding of their difference in evaluating the overall and the local compression efficiency.

1. Introduction

As a component of the airbreathing engine, the inlet is responsible for capturing and compressing freestream air to supply a flow with suitable temperature, pressure, and mass flow rate for efficient operation of engine. Hence, the inlet is a critical component which affects significantly the overall cycle efficiency of the entire engine, especially the ramjet and the scramjet engine.

A variety of efficiency parameters have been introduced to describe the efficiency of the inlet compression process. These efficiency parameters are divided into two classes.[1] Class 1 includes parameters that implicitly define the entropy rise associated with the compression process, regardless of the amount of compression, while Class 2 is composed of those parameters that relate the entropy rise to the compression degree.

The total pressure recovery is universally accepted as a meaningful measure of the performance for subsonic and supersonic aircraft engine inlets,[2,3] which indicates the final thrust potential of the air flow. The total pressure recovery belongs to Class 1 mentioned above, and an abundance of theoretical and experimental works has been done to describe its behavior.[4–14] Other similar parameters can be expressed as functions of the total pressure recovery and the incoming flow

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Nomenclature

c_p	specific heat at constant pressure
E_s	entropy rise coefficient
h	specific enthalpy
p	static pressure
R	gas constant
s	specific entropy
T	static temperature
γ	specific heat capacity
ε_c	compression efficiency
η_B	Billig's compression efficiency
η_c	adiabatic compression process efficiency
η_l	compression quality efficiency
π_c	static pressure ratio
σ	total pressure recovery
ψ_c	static temperature ratio

Subscripts

0	entrance of inlet
3	exit of inlet
x	starting point of isentropic compression process

conditions, including adiabatic kinetic energy efficiency, static pressure efficiency, and dimensionless entropy rise, and they also belong to Class 1.[1,15,16]

However, higher compression degree for inlet design generally leads to lower total pressure recovery.[17,18] Thus, the total pressure recovery and other efficiency parameters in Class 1 cannot comprehensively evaluate the inlet compression efficiency on their own. Parameters in Class 2, such as thermodynamic efficiency, adiabatic compression process efficiency, Billig's compression efficiency, and entropy rise efficiency,[1,15,16] can be expressed via total pressure recovery and static pressure ratio under the hypothesis of a calorically perfect gas, and they may have more valuable implications than parameters in Class 1.

An issue is raised as to how to compare the compression quality of the inlets with different compression degrees or how to evaluate different design methods (they generally generate inlets with different pressure ratios). Obviously, the parameters in Class 1 can only be used to compare the inlet compression quality with the same compression degree. For the inlets with different amount of compression, it is unclear whether the parameters in Class 2 can be directly used as the indicators even though they reflect the flow loss coupled with compression ratio. Hereafter, the heat loss during the compression process is not taken into account, that is to say, the inlet compression is assumed to be adiabatic.

2. Mathematical derivation of efficiency parameters with self-consistency

Essentially, we need to compare the compression quality of different inlets at a unified scale. We thus need to find an inlet compression efficiency parameter in Class 2, which can characterize the quality of the compression process, while remaining independent of the compression degree. It ought to be an invariant in the evaluation of overall compression and local compression for an equal intensity shocks system, e.g., it should meet the self-consistency requirement.

Suppose a specific inlet is made up of a series of child compression processes, which have the same compression efficiency ε_c, the overall compression efficiency of the inlet should also be ε_c according to the physical description of the self-consistency requirement. It must be a function of entropy rise and static pressure ratio. Thus the total pressure recovery can be expressed as a function of the efficiency ε_c and the static pressure ratio, and thus the total pressure recovery of the whole inlet can be written in the form of

$$\sigma\left(\prod_i \pi_{ci}, \varepsilon_c\right) = \prod_i \sigma_i(\pi_{ci}, \varepsilon_c) \quad i = 1, 2, 3, \cdots \tag{1}$$

Take natural logarithm of both sides, we get

$$\ln\sigma\left(\prod_i \pi_{ci}, \varepsilon_c\right) = \sum_i \ln\sigma_i(\pi_{ci}, \varepsilon_c) \quad i = 1, 2, 3, \cdots \tag{2}$$

where i denotes the ith child compression process.

Now convert the static pressure ratio, one of the independent variables in Eq. (2), to a logarithmic form, and the equation can thus be rewritten as

$$\ln\sigma\left(\sum_i \ln\pi_{ci}, \varepsilon_c\right) = \sum_i \ln\sigma_i(\ln\pi_{ci}, \varepsilon_c) \quad i = 1, 2, 3, \cdots \tag{3}$$

As ε_c is a particular constant, Eq. (3) could be further simplified as

$$y\left(\sum_i x_i\right) = \sum_i y_i(x_i) \quad i = 1, 2, 3, \cdots \tag{4}$$

where $y = \ln\sigma, x = \ln\pi_c$.

Intuitively, a linear mapping, $y(x) = L \cdot x$, where L represents a linear operator, can appropriately describe the relation of x to y. For the sake of simplicity and without loss of generality, the linear mapping can be defined as a direct proportional function, denoted as

$$y(x) = \alpha \cdot x \tag{5}$$

where α is the coefficient of proportionality, a function of efficiency ε_c. As a result, the relation between total pressure recovery and static pressure ratio can be expressed as

$$\ln\sigma = \alpha(\varepsilon_c) \cdot \ln\pi_c \tag{6}$$

If $\alpha(\varepsilon_c) = -\varepsilon_c$, then

$$\varepsilon_c = -\frac{\ln\sigma}{\ln\pi_c} = \frac{\Delta s}{R\ln\pi_c} \tag{7}$$

ε_c in Eq. (7) is named here as the entropy rise coefficient, E_s, which represents the entropy rise at unit compression.

And if $\alpha(\varepsilon_c) = 1 - \frac{1}{\varepsilon_c}$, then

$$\varepsilon_c = \frac{\ln \pi_c}{\ln \pi_c - \ln \sigma} \tag{8}$$

ε_c in Eq. (8) is named here as the compression quality efficiency, η_l.

The compression quality efficiency in Eq. (8) and the entropy rise coefficient in Eq. (7) are one–one correspondence, $\eta_l = \frac{1}{1+E_s}$, and they have essentially the same mathematic meaning except for their difference in the selection of coefficient of proportionality, $\alpha(\varepsilon_c)$. But the compression quality efficiency ranging from 0 to 1 could specify the compression efficiency more lucidly, with 0 representing an ineffective compression (pressure ratio doesn't rise but entropy increases) and 1 representing the isentropic compression. Note that, both the entropy rise coefficient and the compression quality efficiency meet the self-consistency requirement.

The two efficiency parameters could also be applied to the general inlet compression processes to evaluate the flow loss caused by the shocks and the boundary layer. Although the same compression efficiency for each child compression in the inlet are not realized in the practical inlet design, the two efficiency parameters mentioned above can be regarded as the indicators of the average compression efficiency for all micro-compression processes of the entire inlet.

3. Discussion on compression efficiencies for shock systems

3.1. Efficiencies for an equal intensity shocks system

An equal intensity shocks system is introduced to facilitate discussions on the self-consistency of the above two parameters. The system is composed of several discrete oblique shocks with the same intensity (i.e., the normal Mach number is the same for all shocks).[3,19,20] In fact, most of inlets are designed approximately as an equal intensity shocks system. As the static pressure ratio and the total pressure recovery are identical across each shock, each compression process via the shock has the same compression quality. Denote the static pressure ratio and the entropy rise of each shock in equal intensity shocks system asπ_{c0} and Δs_0. When an incoming flow passes through these equal intensity shocks successively, its static pressure ratio, entropy rise and efficiency parameters relative to its initial state are shown in Table 1.

The static pressure ratio grows exponentially while the entropy rise is proportional to shock numbers. The entropy rise coefficient and the compression quality efficiency can be found to be invariants, i.e., equal to those of a single shock. Billig's compression efficiency[11] and the adiabatic compression process efficiency,[1] also called process efficiency, are calculated for comparison and listed in Table 1. For a calorically perfect gas, these two efficiency parameters can be expressed as a function of the total pressure recovery and the static pressure ratio

$$\eta_B = \frac{\pi_c^{\frac{\gamma-1}{\gamma}} \cdot \left(1 - \sigma^{\frac{\gamma-1}{\gamma}}\right)}{\pi_c^{\frac{\gamma-1}{\gamma}} - \sigma^{\frac{\gamma-1}{\gamma}}} \tag{9}$$

$$\eta_c = \frac{\pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\pi_c^{\frac{\gamma-1}{\gamma}} - \sigma^{\frac{\gamma-1}{\gamma}}} \tag{10}$$

The expressions in Table 1 are the transformations of Eq. (9) and Eq. (10). It is apparent that Billig's compression efficiency and the process efficiency are not invariants for the equal intensity shocks system, that is, they cannot self-consistently reflect the overall and local compression efficiency, though they take into account the effect of static pressure ratio. As a matter of fact, they concerns more about the overall compression efficiency of the inlet. Similarly, other efficiency parameters in Class 2, such as thermodynamic efficiency, have the same self-consistency problem.

3.2. Comparison of efficiency parameters for different compression systems

In order to check the compression efficiencies of different compression systems at Mach number 6.0, three equal-intensity-shock systems have been taken as examples. In the equal-intensity-shock system, the total pressure recovery and the static pressure ratio across each shock are identical (i.e., the normal Mach number is the same for all shocks). As shown in Fig. 1, there are three shocks with the first ramp angle of 7° in Case 1, and five shocks with the first ramp angle of 7° in Case 3. Case 2 includes five shocks with the first ramp angle of 8°.

It can be noted in Table 2 that three compression systems have different pressure ratios and different total pressure recoveries. In general, higher pressure ratio results in larger total pressure loss. It is difficult to judge the compression quality by examining the indicator of total pressure recovery alone. As efficiency parameters in Class 2, both the process efficiency and the compression quality efficiency relate the total pressure loss to the static pressure ratio. Compared to Case 1, the process efficiency of Case 2 is higher. Nevertheless the compres-

Table 1 Properties of the flow after *i* equal intensity shocks.

Shock No.	1	2	...	N
Static pressure ratio π_c	π_{c0}	${\pi_{c0}}^2$	...	${\pi_{c0}}^N$
Entropy rise Δs	Δs_0	$2\Delta s_0$	...	$N\Delta s_0$
Entropy rise coefficient E_s	$\frac{\Delta s_0}{R \ln \pi_{c0}}$	$\frac{\Delta s_0}{R \ln \pi_{c0}}$	...	$\frac{\Delta s_0}{R \ln \pi_{c0}}$
Compression quality efficiency η_l	$\frac{R \ln \pi_{c0}}{R \ln \pi_{c0} + \Delta s_0}$	$\frac{R \ln \pi_{c0}}{R \ln \pi_{c0} + \Delta s_0}$	...	$\frac{R \ln \pi_{c0}}{R \ln \pi_{c0} + \Delta s_0}$
Billig's compression efficiency η_B	$\frac{\pi_{c0}^{\frac{\gamma-1}{\gamma}} \cdot (1 - e^{-\frac{\Delta s_0}{C_p}})}{\pi_{c0}^{\frac{\gamma-1}{\gamma}} - e^{-\frac{\Delta s_0}{C_p}}}$	$\frac{\pi_{c0}^{\frac{2\gamma-2}{\gamma}} \cdot (1 - e^{-\frac{2\Delta s_0}{C_p}})}{\pi_{c0}^{\frac{2\gamma-2}{\gamma}} - e^{-\frac{2\Delta s_0}{C_p}}}$	...	$\frac{\pi_{c0}^{\frac{N(\gamma-1)}{\gamma}} \cdot (1 - e^{-\frac{N\Delta s_0}{C_p}})}{\pi_{c0}^{\frac{N(\gamma-1)}{\gamma}} - e^{-\frac{N\Delta s_0}{C_p}}}$
Process efficiency η_c	$\frac{\pi_{c0}^{\frac{\gamma-1}{\gamma}} - 1}{\pi_{c0}^{\frac{\gamma-1}{\gamma}} - e^{-\frac{\Delta s_0}{C_p}}}$	$\frac{\pi_{c0}^{\frac{2\gamma-2}{\gamma}} - 1}{\pi_{c0}^{\frac{2\gamma-2}{\gamma}} - e^{-\frac{2\Delta s_0}{C_p}}}$	...	$\frac{\pi_{c0}^{\frac{N(\gamma-1)}{\gamma}} - 1}{\pi_{c0}^{\frac{N(\gamma-1)}{\gamma}} - e^{-\frac{N\Delta s_0}{C_p}}}$

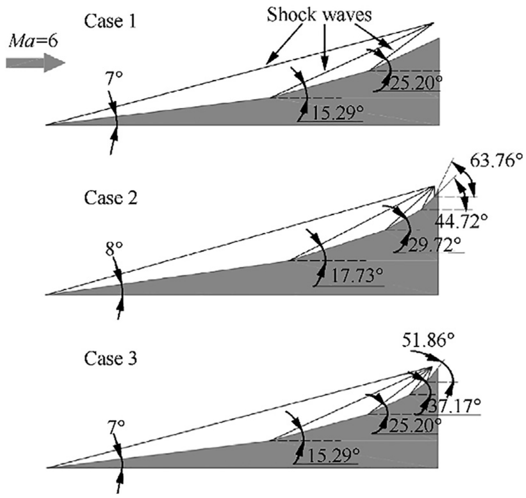

Fig. 1 Diagrams of equal-intensity-shock systems.

Table 2 Performance of different compression systems.

Case No.	1	2	3
Static pressure ratio π_c	17.33	211.73	116.05
Total pressure recovery σ	0.773	0.544	0.651
Entropy rise coefficient E_s	0.090	0.114	0.090
Compression quality efficiency η_l	0.917	0.898	0.917
Billig's compression efficiency η_B	0.120	0.195	0.149
Process efficiency η_c	0.947	0.957	0.962

sion quality efficiency exhibits an opposite trend. Apparently, the compression quality of the shock system in Case 2 should be admittedly poorer because the total pressure loss in Case 2 is larger for each shock. So we can argue that the process efficiency cannot evaluate the compression quality of the inlets with different compression degrees.

As to Case 1 and Case 3, the flow compression is designed with the same quality because each shock is characterized by the same pressure ratio and entropy rise. The compression quality efficiency reveals this characteristic, while the process efficiency has different values because of the self-consistency problem. And Billig's compression efficiency, listed in Table 2, also has the problems as the process efficiency does. Thus, these two efficiency parameters may be unfit for comparing the quality of compression processes of the inlets with different compression degrees. They reflect the compression efficiency of the entire inlet.

4. Mechanism of self-consistency for compression quality efficiency

It has been proven in mathematics that both the compression quality efficiency and the entropy rise coefficient can self-consistently reflect the overall and the local compression efficiency of the inlet. But the adiabatic compression process efficiency doesn't possess this property. In this section, the Mollier diagram of the inlet compression process is taken into account to elucidate the mechanism.

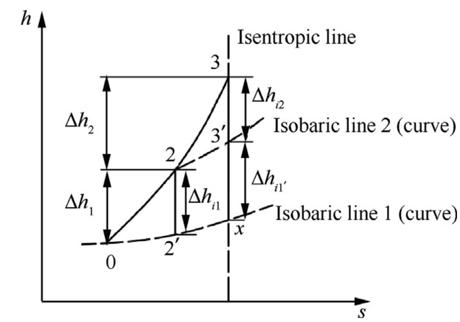

Fig. 2 Mollier diagram of process efficiency.

Let us first analyze the process efficiency. As shown in Fig. 2, assume that the compression process 0–2 has the same process efficiency value as the compression process 2–3. According to the definition of the process efficiency,[1]

$$\eta_{c1} = \frac{\Delta h_{i1}}{\Delta h_1} = \frac{\Delta h_{i2}}{\Delta h_2} = \eta_{c2} \tag{11}$$

And the formula of isobaric line 1 and isobaric line 2 in Fig. 2 can be expressed as

$$h = h_{2'} \cdot \exp\left[\tfrac{\gamma-1}{\gamma R}(s - s_2)\right] \tag{12}$$

$$h = h_2 \cdot \exp\left[\tfrac{\gamma-1}{\gamma R}(s - s_2)\right] \tag{13}$$

Combining Eq. (12) and Eq. (13), we can derive

$$\begin{aligned}\frac{\Delta h_{i1'}}{\Delta h_{i1}} &= \frac{h_{3'} - h_x}{h_2 - h_{2'}} \\ &= \frac{h_2 \cdot \exp\left[\tfrac{\gamma-1}{\gamma R}(s_3 - s_2)\right] - h_{2'} \cdot \exp\left[\tfrac{\gamma-1}{\gamma R}(s_3 - s_2)\right]}{h_2 - h_{2'}} \\ &= \exp\left[\tfrac{\gamma-1}{\gamma R}(s_3 - s_2)\right] > 1\end{aligned} \tag{14}$$

In other words, $\Delta h_{i1'} > \Delta h_{i1}$, that is, the longitudinal spacing between the two isobaric lines in Fig. 2 will continue to expand with the increase of entropy. Thus, the process efficiency of the whole inlet is

$$\eta_c = \frac{h_3 - h_x}{h_3 - h_0} = \frac{\Delta h_{i1'} + \Delta h_{i2}}{\Delta h_1 + \Delta h_2} > \frac{\Delta h_{i1} + \Delta h_{i2}}{\Delta h_1 + \Delta h_2} = \eta_{c1} = \eta_{c2} \tag{15}$$

Eq. (15) helps clarify the reason why the process efficiency is not capable of meeting the demand of self-consistency.

For ease of comparison of the two efficiency parameters, the compression quality efficiency is transformed into a new form similar to the definition of process efficiency.

As

$$\Delta s = c_p \ln \psi_c - R \ln \pi_c \tag{16}$$

and rewrite

$$\eta_l = \frac{1}{1 + \Delta s/(R \ln \pi_c)} = \frac{\gamma - 1}{\gamma} \cdot \frac{\ln \pi_c}{\ln \psi_c} \tag{17}$$

For the isentropic compression process from Point x to Point 3, the static pressure ratio can be expressed as

$$\pi_c = \frac{p_3}{p_0} = \frac{p_3}{p_x} = \left(\frac{T_3}{T_x}\right)^{\frac{\gamma}{\gamma-1}} \tag{18}$$

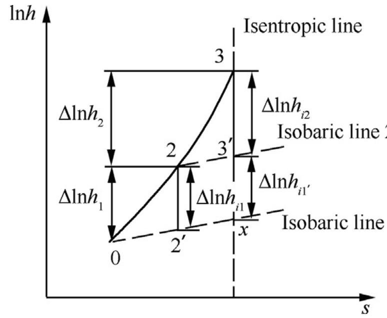

Fig. 3 Mollier diagram of compression quality efficiency.

By substituting Eq. (18) into Eq. (17), a new formula of the compression quality efficiency for compression process 0–3 could be obtained as

$$\eta_1 = \frac{\gamma-1}{\gamma}\cdot\frac{\ln\pi_c}{\ln\psi_c} = \frac{\ln(T_3/T_x)}{\ln(T_3/T_0)} = \frac{\ln(h_3/h_x)}{\ln(h_3/h_0)} = \frac{\ln h_3 - \ln h_x}{\ln h_3 - \ln h_0} \tag{19}$$

In Fig. 3, the longitudinal coordinate is $\ln h$ according to Eq. (19). Assume that the compression process 0–2 and the compression process 2–3 have the same compression quality efficiency, that is

$$\eta_{11} = \frac{\Delta\ln h_{i1}}{\Delta\ln h_1} = \frac{\Delta\ln h_{i2}}{\Delta\ln h_2} = \eta_{12} \tag{20}$$

Now turn to the two isobaric lines in the new Mollier diagram in Fig. 3, their formulas become

$$\ln h = \ln h_2 + \frac{\gamma-1}{\gamma R}(s-s_2) \tag{21}$$

$$\ln h = \ln h_{2'} + \frac{\gamma-1}{\gamma R}(s-s_2) \tag{22}$$

It can be easily concluded that the isobaric lines are both straight lines and have the same slope, $\frac{\gamma-1}{\gamma R}$. Therefore, the longitudinal spacing between the two lines doesn't expand with the increase of entropy, $\Delta\ln h_{i1} = \Delta\ln h_{i1'}$. Hence, for the compression process 0–3 of the inlet

$$\eta_1 = \frac{\ln h_3 - \ln h_x}{\ln h_3 - \ln h_0} = \frac{\Delta\ln h_{i1'} + \Delta\ln h_{i2}}{\Delta\ln h_1 + \Delta\ln h_2} = \frac{\Delta\ln h_{i1} + \Delta\ln h_{i2}}{\Delta\ln h_1 + \Delta\ln h_2} = \eta_{11} = \eta_{12} \tag{23}$$

Eq. (23) proves that the compression quality efficiency meets the self-consistency requirement. Intuitively, it is because the definition formula of the compression quality efficiency in Eq. (19) takes the logarithmic form of static enthalpy compared to process efficiency, which turns the isobaric lines into straight lines in the new Mollier diagram. This comparison facilitates a clearer understanding of the two efficiency parameters.

5. Conclusions

The inlet is a critical component of an airbreathing engine, and a lot of efficiency parameters have been defined to evaluate its compression efficiency. The parameters are studied in this paper for evaluating the compression quality of the inlets with different compression degrees. In order to measure the inlet compression quality at a unified scale, the property of self-consistency is demanded for efficiency parameters, which characterize the inlet compression quality independent of the compression degree.

Two new efficiency parameters, compression quality efficiency and entropy rise coefficient, are derived mathematically to represent the average compression efficiency of the entire inlet. By comparison with adiabatic compression process efficiency for an equal intensity shocks system, they have been proven capable of characterizing the quality of compression system, while the process efficiency is unfit for evaluating the compression quality of the inlets with different compression degrees, though it reflects the flow loss coupled with compression ratio. Furthermore, the process efficiency and the compression quality efficiency are analyzed in the Mollier diagram to elucidate the mechanism of their difference. It is revealed that the self-consistency of the compression quality efficiency results essentially from taking the logarithm form of static enthalpy in its definition formula, which turns the isobaric lines into straight lines in the new Mollier diagram.

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