The Effect of Heat Transfer on Turbine Performance

By Lachlan J. Jardine and Robert J. Miller, Whittle Laboratory, University of Cambridge

What’s the Problem?

For over 50 years, high-pressure gas turbine blades have been cooled using air bled from the compressor. This cooling results in very high rates of heat transfer, both within the fluid and within the blade, shown in figure 1. The heat transfer often occurs across large temperature differences and is thus highly irreversible. It is therefore surprising that little is understood about the effect of this heat transfer on turbine performance.

The New Approach

The new approach was developed by Miller [4] and is known as mechanical work potential, or euergy. This method is based on the simple idea that the ideal work, to which a turbine designer aspires, is the work that can be extracted by a reversible adiabatic turbine (i.e. a reversible adiabatic expansion to the fixed exhaust pressure). A key consequence of this method is that the value of all heat, in terms of the work that can be extracted from it, is set by the Joule (Brayton) cycle efficiency. This result can be easily shown using the simple example in figure 2. A small heat addition, $d\dot{Q}$, is transferred to the flow of a perfect gas. The ideal method of work extraction is defined as the work that can be extracted by a reversible adiabatic turbine exhausting to an environmental pressure, $p_0$. The increase in the rate of work is:

$$d\dot{W} = \left[1 - \left(\frac{p}{p_0}\right)^{\frac{\gamma - 1}{\gamma}}\right] d\dot{Q}$$

More generally, if an euergy approach is taken then the value placed on all heat addition, locally within the flow, is set by the Joule (Brayton) cycle efficiency.

The Difference Between the Traditional and New Approaches

The fundamental difference between the two approaches is the ideal work to which a turbine designer aspires. The exergy (entropy) method is based on the idea that the ideal work is the work that can be extracted by a universal reversible...
machine which can bring the flow to the pressure and temperature of the environment. To achieve this, a reversible adiabatic turbine is required to bring the flow to the environmental pressure, $p_0$, and a reversible heat engine is required to bring the flow to the environmental temperature, $T_0$. In contrast, the euergy method is based on the idea that the ideal work is the work that can be extracted by a reversible adiabatic turbine which can bring the flow to the environmental pressure only. The exhaust of the turbine is at a temperature that differs from the temperature of the environment. The extra work that could be extracted from it is considered lost in the exhaust.

The key consequence of this choice of method is the value placed on heat. For the euergy method, the value placed on all heat is set by the Joule cycle efficiency. For the exergy method, the value placed on all heat is set by the Carnot cycle efficiency.

$$dW = \left(1 - \frac{T_0}{T}\right) d\dot{Q}$$

The euergy method represents the true aspiration of the turbomachinery designer (to design reversible adiabatic turbomachines).

**The Recuperation Effect**

The new approach shows that heat transfer within the blade row can act to reduce the loss coefficient of a blade row (i.e. raise stage efficiency). This may at first seem strange. The physical mechanism responsible for this effect can be understood by considering a small heat flux, $d\dot{Q}$, passed between two streams of a perfect gas. If the pressure of the hot stream is lower than the pressure of the cold stream, then heat is transferred from a low to a high Joule cycle efficiency. This increases the rate of work which can be extracted from the flow by

$$dW = \left(\frac{p_0}{p_{\text{low}}}\right)^{\frac{T-1}{T}} - \left(\frac{p_0}{p_{\text{high}}}\right)^{\frac{T-1}{T}} d\dot{Q}$$

The increase in work that can be extracted from the flow comes from a recovery of energy from the hot turbine exhaust. The effect can be thought of as a form of recuperation, a recovery of energy which would otherwise have been wasted in the turbine exhaust.

**Impact of Heat Transfer**

Jardine and Miller [5] showed the impact of heat transfer on turbine performance, shown in figure 3. As the ratio of mainstream-to-coolant temperature ratio is increased, the exergy method shows the blade loss rises by 60%. The euergy method however shows that the blade loss falls by 3.6%. The fall is the result of the recuperation effect. The euergy method exhibits the experience of industrial designers; that heat transfer does not have a large effect on efficiency.

![](image)

**Figure 3. Comparison of Exergy and Euergy Loss Coefficients**

**Implications**

The recuperation effect offers a new way of raising turbine efficiency. Jardine and Miller [5] show that, by moving from externally to internally cooled blades, a potential reduction of blade loss of ~7% can be achieved. Now that a systematic method of analysing cooled component performance has been developed, we have the exciting opportunity to undertake a truly aerothermal optimisation of the new, and highly complex, cooling geometries enabled by additive manufacture.

The euergy method also offers a new way to analyse air-breathing engines, i.e. engines which exhaust to a fixed environment pressure. For such devices the euergy method should be used to guide design, while the more traditional exergy method should be used as a measure of the upper efficiency limit of the engine.

---

1 Euergy from the Greek eu and ergon meaning good or useful work. The ‘eu’ is pronounced as in eulogy, in the classical Greek pronunciation.

1 Horlock, J. H., 2001. “The basic thermodynamics of turbine cooling”. ASME J. Turbomach., 123(3), pp. 583–592.
2 Denton, J. D., 1993. “Loss mechanisms in turbomachines”. ASME J. Turbomach., 115(4), p. 621.
3 Young, J. B., and Wilcock, R. C., 2002. “Modeling the air-cooled gas turbine: part 2—coolant flows and losses”. ASME J. Turbomach., 124(2), p. 214.
4 Miller, R. J., 2013. “Mechanical work potential”. In Proceedings of ASME Turbo Expo 2013: Power for Land, Sea and Air. Paper No. GT2013-95488.
5 Jardine, L. J., and Miller, R. J., 2019. “The effect of heat transfer on turbine performance”. In Proceedings of ASME Turbo Expo 2019: Power for Land, Sea and Air. Paper No. GT2019-91556.