# Convective meta-thermal concentration for Stirling engine

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## I. Introduction

The Stirling engine possesses several advantages, including external combustion characteristics, a simple structure, and high theoretical thermal efficiency. Extensive research has been conducted on its potential for waste heat and cold utilization, which can greatly enhance energy efficiency [1]. However, the engine suffers from thermal inefficiency due to the temperature variations in practical heat-exchanging fluids [2-4]. To address this issue, convective meta-thermal concentration (CMTC) was introduced in this study as a means of improving the Stirling engine system. By increasing the temperature difference between the hot and cold ends, a significant improvement in the engine's efficiency was achieved.

## II. Theoretical analysis

Fig. 1(a) shows a Stirling engine system integrated with CMTC. A more detailed relationship between input [output] heat flux $\dot{Q}_{\mathrm{HE}}^{u}[\dot{Q}_{\mathrm{CE}}^{u}]$ and the temperature of the working substance on the hot [cold] end $T_{\mathrm{HE}}^{u}[T_{\mathrm{CE}}^{u}]$ is presented in Fig. 1(b). Note that, $u=\mathrm{Cl}$ and $u=$TCP represents the shells of the heat and cooler are made by classical high thermal conductivity materials (Cl shell) and high-low thermal conductivity materials alternatively arranged [Thermal conductivity platter (TCP) shell], respectively. Compared with the Cl shell, the TCP shell uses equivalent anisotropic thermal conductivity to concentrate heat flow, thereby acting as CMTC. By implementing CMTC, the hot/cold end temperature can be increased/decreased [Fig. 1(c)]. Coupling this effect into the Stirling engine system, the engine power could be improved [Fig. 1(d)]. Assuming the Stirling engine undergoes an internal reversible cycle, its thermal efficiency reads

$$\eta_u = 1 - \frac{T_{\mathrm{CE}}^{u}\left(\dot{Q}_{\mathrm{CE}}^{u}\right)}{T_{\mathrm{HE}}^{u}\left(\dot{Q}_{\mathrm{HE}}^{u}\right)}.$$

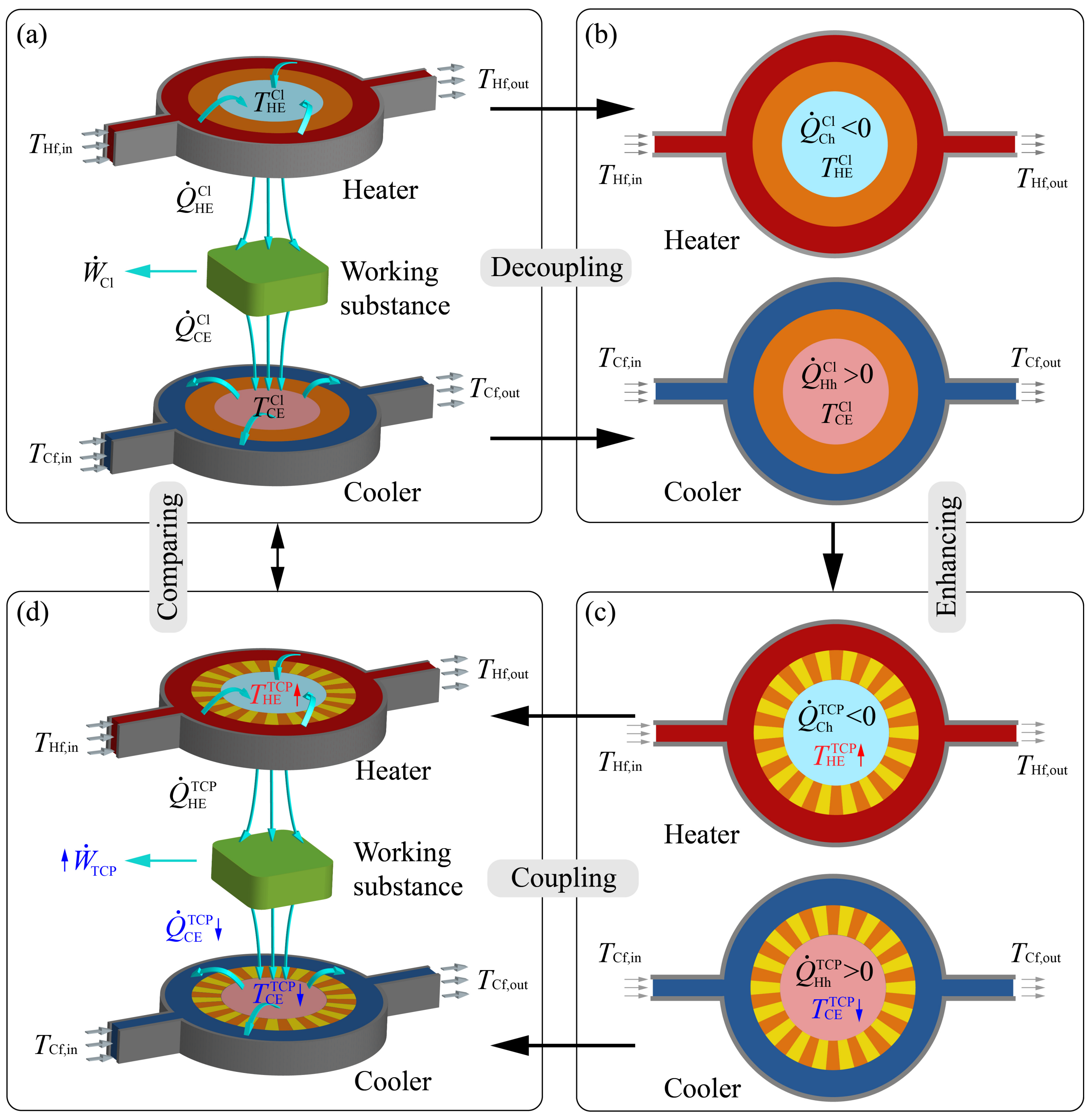

Fig. 1. Schematic diagram of the Stirling engine system with and without CMTC [5].

Define heating and cooling enhancement coefficients as $\alpha = T_{\mathrm{HE}}^{\mathrm{TCP}}/T_{\mathrm{HE}}^{\mathrm{Cl}}$ and $\beta = T_{\mathrm{CE}}^{\mathrm{TCP}}/T_{\mathrm{CE}}^{\mathrm{Cl}}$, respectively. The thermal efficiency improvement magnitude from the Stirling engine without CMTC to that with CMTC can be expressed as

$$\zeta = \frac{\eta_{\mathrm{TCP}} - \eta_{\mathrm{Cl}}}{\eta_{\mathrm{Cl}}} = \left(\frac{1}{\eta_{\mathrm{Cl}}} - 1\right)\left(1 - \frac{\beta}{\alpha}\right).$$

When $\dot{Q}_{\mathrm{HE}}^{u}$ is large enough, the Stirling engine efficiency without CMTC ($\eta_{\mathrm{Cl}}$) will tend to 0 quickly due to the fast closing of $T_{\mathrm{HE}}^{\mathrm{Cl}}$ and $T_{\mathrm{CE}}^{\mathrm{Cl}}$. At this time, if CMTC plays a significant role, making $\alpha \gg 1$ and $\beta \ll 1$, $\zeta$ will tend to $\infty$. Then, an ultrahigh thermal efficiency improvement can be realized.

## III. Results and discussion

We calculated the Stirling engine efficiency with and without CMTC under specific operating conditions, as shown in Fig. 2. When $\eta_{\mathrm{Cl}} \to 0$, $\zeta \to 900\%$, which is in great consistent with the theoretical prediction.

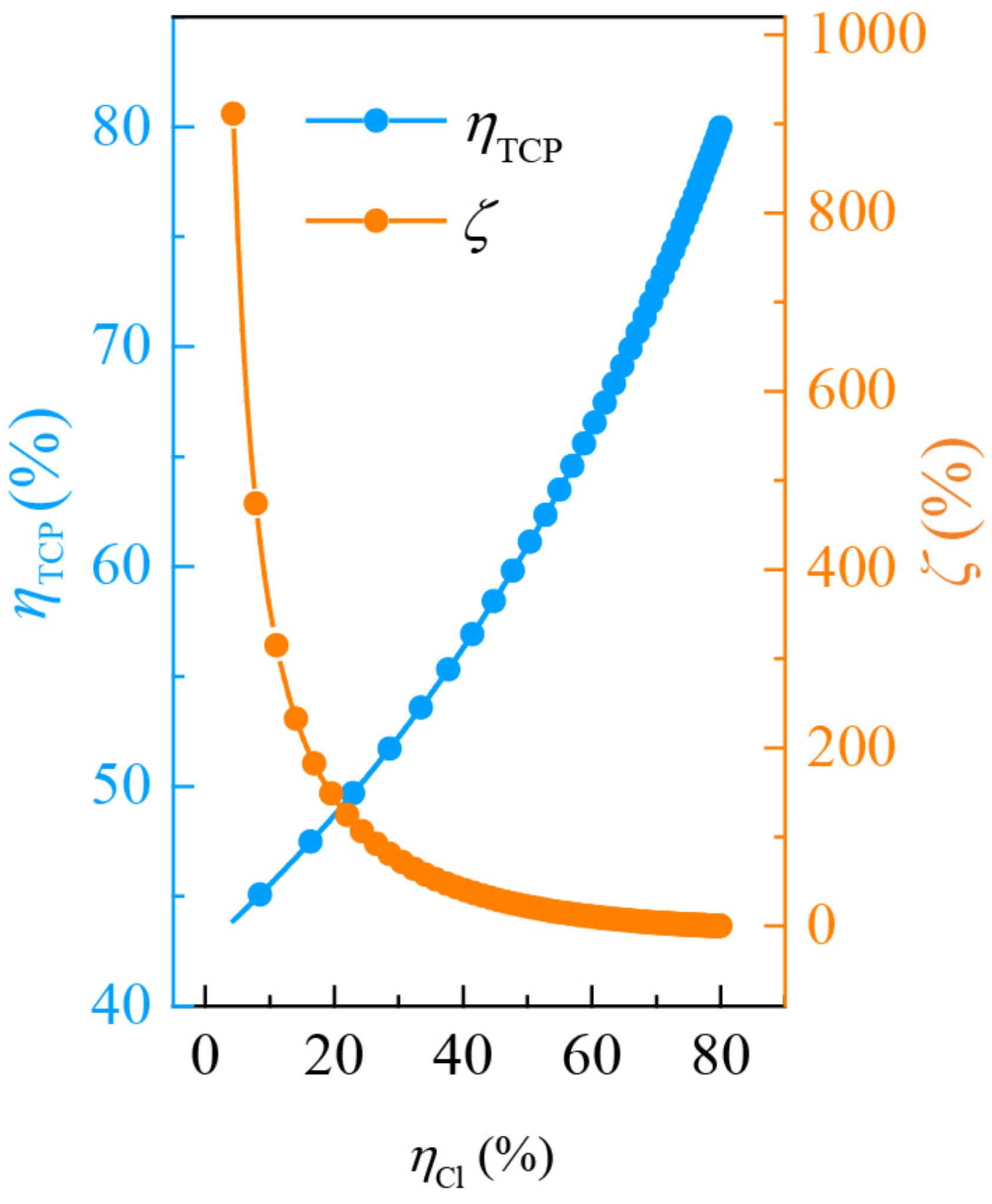

Fig. 2. Effect of CMTC on Stirling engine efficiency improvement [5].

It shows that when the Stirling engine efficiency is constrained by finite waste heat and cold resources, the integration of CMTC plays a crucial role in overcoming these limitations. This operation offers an exciting avenue for sustainable energy utilization.

## IV. Conclusions

- CMTC significantly increases the temperature difference between both ends of the Stirling engine.
- When $\eta_{\mathrm{Cl}}$ is low due to the finite waste heat and cold resources, CMTC exhibits great potential for enhancing the Stirling engine efficiency.
- More operation conditions should be performed to further reveal the effect of CMTC for practical applications.

References:

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