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ABSTRACT

With the application of the dynamic equations of state of working fluids that involve in addition to the system parameters the environmental ones as well, the thermodynamic power cycles with a gas-dynamic and thermal regeneration are described from the standpoint of the dynamic equilibrium method. Using the methods of the gas-dynamic regeneration based on controlling the adiabat trajectories owing to a combination of quasi-static and dynamic processes allows the investigation of the cycles which have no thermal release into the environment. In this case the energy of working fluid compression at closing the cycle is transformed not into the heat energy as usually but into the kinetic one of the working fluid. Though such cycles have the conventional performance of Carnot cycle, they can be used in any temperature range involving the range being lower than the temperature level of the environment for transforming the cold energy into the mechanical one. The combination of the dynamic and thermal regeneration methods provides additionally a possibility of enhancing the efficiency of the cycle. In the refrigeration cycles the employment of the dynamic regeneration can also assist in increasing the technological efficiency.

1. INTRODUCTION

From the standpoint of classical thermodynamics based on the quasi-static equilibrium method it is usually suggested that the reverse cycles in which the thermal energy is converted to a higher temperature level due to the consumption of mechanical power are necessary for the cold production. At the same time, the refrigeration effects of the direct cycles in which the refrigeration occurs owing to the conversion of thermal energy into mechanical power are limited only by the range of temperatures exceeding the environment level.

However, from the standpoint of a different thermodynamic method, i.e. the dynamic equilibrium method, the use of the refrigeration effects of the direct cycles is feasible also at the temperatures being lower than the environment level.

It has been shown that the peculiarity of this method is the application of the dynamic equations of state that include in addition to the ordinary (static) parameters of state of a system the environmental parameters or running process rates (Samkhan, 2000). These equations of state coincide with the traditional static ones in the absence of a potential difference between a system and the environment. Moreover, they correlate with the energy balance equations and with the d'Alembert-Lagrange's principle relating to the statics/dynamics ratio in the engineering mechanics.

Due to the application of such equations the possibility arises of treating the behavior of the externally nonequilibrium thermodynamic systems characterized by the availability of some potential difference with the environment as that of the equilibrium ones.

Previously, special cases of the dynamic equations of state, as applied to ideal gases and gas-vapor mixtures, were considered from the standpoint of this method (Samkhan, 2001, 2003, 2003). And, in particular, the dependence of adiabatic exponents on the flow velocities of the working fluids and on their internal structure, the admissibility of adiabat trajectory intersection in various coordinate systems and the possibility of investigation of the ideal regenerative cycles with equivalent conversions of thermal and mechanical energy were demonstrated thereby.

It was also shown there that these facts do not contradict well-known constraints of the second law of thermodynamics provided that the corresponding temperatures of the heat sources, commonly used in this case, are substituted by the corresponding (appropriate) temperatures of the working fluid, and the entropy is regarded as one of the heat capacity forms, the possibility of what was demonstrated earlier (Samkhan, 1996).

In this paper we deal with additional techniques for controlling gas-flow adiabats and investigate the performance of a new closed power cycle with gas-dynamic and thermal regeneration.

2. EQUATIONS OF GAS-FLOW ADIABATS

The equations of state for an ideal gas flow with one degree of nonequilibrium ($\Delta p \neq 0$) can be represented as equations (1) and (2)

$$C_p T = C_v T + pv + w^2 / 2 = C_v T + pv + \Delta pv \tag{1}$$

$$\left[\frac{(k-1)M^2+1}{k-1}\right]\frac{dT}{T} - M^2\frac{dp}{p} = \frac{dq}{a^2} - \frac{dl}{a^2} + M^2\frac{dF}{F} \tag{2}$$

which fit the energy balance equation (3) for gas flow

$$dq = dh + dl + dw^2 / 2 \tag{3}$$

and are transformed into the Clapeyron equation $pv = RT$ for quasi-static systems with the proviso that $M \to 0$. In these equations T, p, v, C_p and C_v are temperature pressure, specific volume, specific heat capacity of a gas at $p = const$ and $v = const$, correspondingly; R is gas constant, a is sonic speed, ? is flow velocity, M is Mach number, Δp is differential pressure of a static system and surroundings, k is index of a quasi-static adiabat, F is cross–section of a flow; q, l, h are specific values of heat flows, technical work and enthalpy, correspondingly.

Under Equation (3), the gas flow adiabats determined by the condition $dq = 0$ may be represented in terms of Equation (4)

$$dh = dl + dw \tag{4}$$

involving Poisson adiabat $dh = dl$ and Bernoulli adiabat $dh = dw_v$, where dw and dw_v are elementary changes of specific kinetic energy of the flow in general case and with the proviso that $v = (1/r) = const$, where r is flow density. From Equation (4) follows that the adiabat trajectories can be controlled through the combination of Poisson and Bernoulli adiabats. Particularly, with the work being equal to change in kinetic energy $dl = dw$, the adiabat will take the form of an isotherm, which according to Equation (2) may be represented by Equation (5)

$$dp / p = -\left[kM^2 / \left(kM^2 \pm 1\right)\right] \left(dF / F\right) \tag{5}$$

Besides, from Equation (2) other special cases follow too. In particular, if $dq = 0$ and $M \to 0$, we have Poisson adiabat (6)

$$pv^k = const \tag{6}$$

for quasi-static processes, while if $dq = 0$, $dl = 0$ and $r = const$, we have the Bernoulli adiabat equation for gas flows (7)

$$\left(\frac{k}{k-1}\right)\frac{dp}{r} = -\frac{dw^2}{2} = w^2\,\frac{dF}{F} \qquad (7)$$

which for liquid fluids having, as is well known (e.g. Kirillin *et al*., 1983), the value $k >> 1$, converts to the previously known Bernoulli formula (8)

$$\frac{\Delta p}{r} + \frac{w^2}{2} = const \qquad (8)$$

The expression (7) can be also derived directly from the energy balance $dh = d\left(w^2/2\right)$, with the proviso that $h = C_p T$, $RT = pv$ and $v = const$.

3. IDEAL CLOSED CYCLE WITH GAS-DYNAMIC AND THERMAL REGENERATION

Using, along with the quasi-static processes, the dynamic ones allows the potentialities of the thermodynamic method to be extended.
By way of example a new ideal regenerative cycle with gas dynamic regeneration whose charts in $h,T-v$ coordinates are depicted in Figure 1 is considered. In this cycle the working fluid (helium) isobarically preheated from the temperature T_2 to T_3 expands adiabatically in the same temperature range with doing work l_1 and then compresses isothermally at the temperature $T_1 < T_2$ with the transformation of the compression work $l_2 < l_1$ not into thermal energy (as usually) but into kinetic energy W (where $l_2 = W$). In its turn this kinetic energy regenerates into the thermal one to partially heat in isobaric way the working fluid to the level T_3. Moreover, in this cycle the transition of the working fluid from the energy level T_2 to T_1 and vice versa is represented by the isochoric regenerative heat exchange processes (as in the Stirling cycle).

It is shown in Figure 1 that the useful work l_{ext} of such a cycle is less than the work l_1 of adiabatic process (3-4) by the quantity l_2 spent for closing (regenerating) the cycle. In a similar manner, the heat q_{ext} consumed from an external source is less than the general heat flow q_1 used in the cycle by the quantity $q_{reg} = l_2$ evolving in the kinetic energy regeneration of the flow $w = l_2$ during the process (6-3).

The relationship between these quantities can be represented by the following expressions:

$$q_{ext} = l_{ext} = C_p(T_3 - T_2 - T_1 \ln T_3 / T_2) \qquad (9)$$

$$q_1 = l_1 = h_3 - h_2 = C_p(T_3 - T_2) = RT_{av}\,\ln(p_3 / p_2) \qquad (10)$$

$$q_{ext} = l_{ext} = q_1 - q_{reg} = l_1 - l_2 \qquad (11)$$

$$q_{reg.} = l_2 = C_p T_1\,\ln(T_3 / T_2) \qquad (12)$$

In Equation (10) it is shown that the work of the adiabatic process running, by definition, with no change of entropy $\Delta S = 0$, may be represented, when using the mean temperature T_{av} , as the work of an isothermal process for which the entropy change has the finite value equal to $\Delta S = q_1 / T_{av} = l_1 / T_{av}$, where

$$T_{av} = (T_3 - T_2) / \ln(T_3 / T_2) \tag{13}$$

In the general case the conventional performance of the thermal efficiency of such a cycle may be expressed by the relative difference of mean temperatures of the adiabatic expansion T_{av} and adiabatic compression T_1 of the working fluid in terms of Equation (14)

$$h = \frac{l_{ext}}{q_1} = \frac{q_{ext}}{q_1} = \left(\frac{T_{av} - T_1}{T_{av}} \right) \tag{14}$$

differing from a similar Carnot cycle equation only by the use in it of temperatures of the processes having no thermal contacts with the environment.

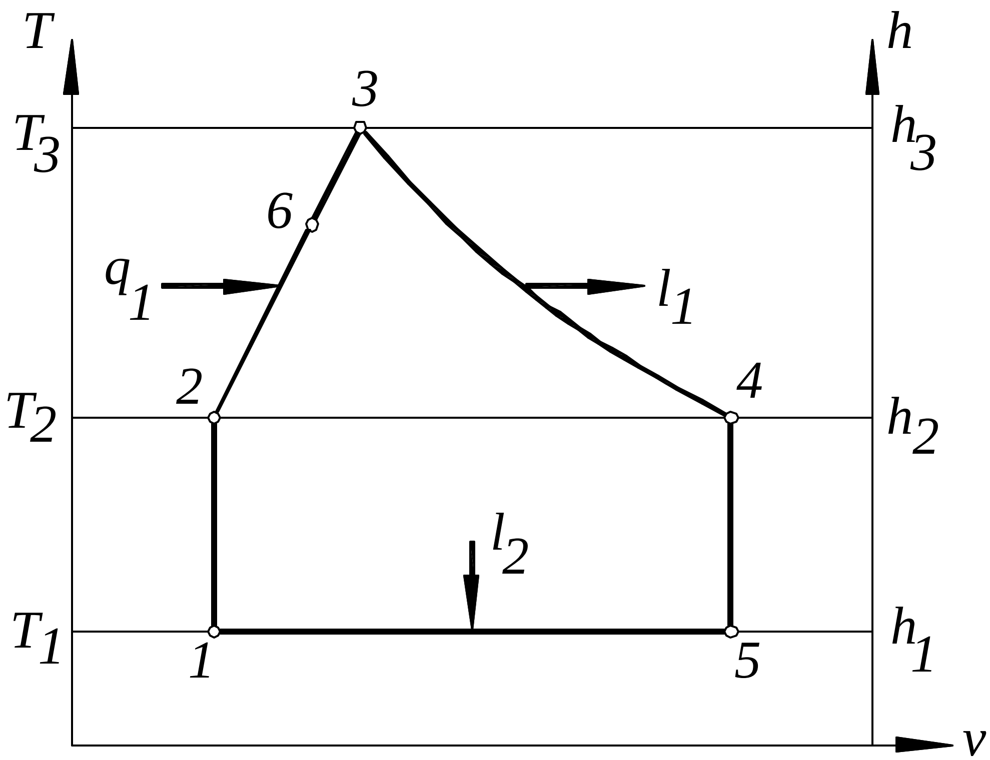

Figure 1: The temperature (T)–enthalpy (h)–volume (v) diagram of the power cycle with gas-dynamic regeneration used for refrigeration

4. DISCUSSION

The dynamic equilibrium method developed here combines essentially two parts of thermodynamics which pertain to the description of quasi-static (static) processes as well as flows running in space and time. The possibility of dynamically controlling the adiabat trajectories, allowable from the standpoint of this method, enables the regenerative cycles without thermal release into the environment to be investigated, and therefore to be applied for both cold production and mechanical power at comparatively low temperatures.

A peculiarity of the type of cycle discussed here is a combination of the processes of gas-dynamic and static regenerations, the latter being carried out by way of isochoric heat exchange (as in the Stirling cycle). These isochoric regenerative heat exchange processes can be also considered as adiabatic ones because they have no thermal contacts with the environment.

The mentioned combination of regenerative processes enables one to increase the efficiency of the cycles when using relatively moderate velocities and pressures of the working fluid.

Thus, for example, let us assume that $T_3 = 300\ K$, $T_2 = 200\ K$ and $T_1 = 100\ K$ as well as $C_p = 5.2\ kJ\ /\ kg\ K$, $R = 2077\ J\ /\ kg\ K$ and $K = 1.66$. Then the conventional efficiency factor (performance of the Carnot cycle) of such a cycle makes up about 0.595, the refrigeration performance q_{ext} and the useful work l_{ext} of the cycle in the temperature range $(T_6 - T_2) = 59.5\ K$ will be equal to $q_{ext} = l_{ext} = 309.4\ kJ\ /\ kg\ K$. In this case the velocity ? of the working fluid defined by the expression

$$\frac{w^2}{2} = l_2 = C_p T_1 \cdot \ln \frac{T_3}{T_2} = RT_1 \cdot \ln \frac{P_1}{P_5} \tag{15}$$

will be at $T_1 = 100\ K\ (588.8\ m\ /\ s)$ only 1.1 times greater than the sonic speed, whereas the pressure ratio defined by the expression

$$l = \frac{P_1}{P_5} = \frac{P_2}{P_4} = \frac{P_3}{P_4} = \left(\frac{T_3}{T_2}\right)^{\frac{K}{K-1}} \tag{16}$$

will amount to a comparatively small value $l = 2.77$.

It should be also noted that the dynamic equilibrium method under discussion can be also used for an essential increase in efficiency of the reverse cycles as well, in which the thermal energy is converted to a higher temperature level.

One of such versions in which a high-velocity vapor-liquid flow is used for regenerating the potential energy of the working fluid is currently developed with the grant RE1-5009-YA-03 by the US Civilian Research and Development Foundation (CRDF).

4. CONCLUSION

Thus the employment of the dynamic models describing heat-mechanic conversions extends the potentialities of the thermodynamic method and points up the availability of additional resources to enhance the efficiency of the low-temperature technologies for generating energy.

REFERENCES

Kirillin, V., Sychev, A., Sheyndlin, A., 1983, *Technical Thermodynamics*, Energoizdat, Moscow (Russia), 416 p.

Samkhan, I., 1996, On the Relationship Between the Specific Heat and Entropy of Thermodynamic Systems, *Physics – Doklady*, vol. 41, no. 1: p. 327–330.

Samkhan, I., 2000, Specific Features of Thermodynamics of Gas Flows, *The 8th International Energy Forum, Las Vegas, 23–28 July 2000,* Balaban Publisher: p. 865–870.

Samkhan, I., 2001, Thermodynamic Processes From a Method of Dynamic Balance. *Russian National Symposium of Power Engineering,* Kazan, Russia, 10-14 September 2001, vol.1: p. 262-265.

Samkhan, I., 2003, New Possibilities for Energy Production From Renewable Low Potential Sources, *Applied Energy*, Elsevier, vol. 74, no. 1–2.

Samkhan, I., 2003, Using Low Temperatures From the Standpoint of the Dynamic Equilibrium Method, *21st IIR International Congress of Refrigeration,* Washington D.C., USA, 17-22 August 2003.