INTEGRATION OF AN ELECTROGASDYNAMIC POWER CONVERTER INTO EJECTOR COOLING SYSTEMS

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Abstract

This study presents a novel incorporation of an electrogasdynamic (EGD) power converter and an ejector system to produce combined cooling and power. The EGD converter offers a direct conversion of heat to electricity by using an electrically charged aerosol. The EGD conversion is accomplished in the main nozzle of the ejector and the remaining kinetic energy of working fluids is used to drive the ejector system. This system has the advantages of no moving parts and simplicity compared with conventional combined systems. The principle of this system is described and a thermodynamic analysis is given in this study. The EGD conversion efficiency may be adjusted by changing the operating current and it is limited by the electric breakdown strength. A larger conversion efficiency at electric breakdown is associated with a larger inlet density of vapors, a smaller specific enthalpy difference of generation and a larger standard electric breakdown strength. The calculation shows that the EGD conversion efficiency would be less than 0.001% for water at 100~140^{o}C generating temperature due to its small electric breakdown strength. If R11 is used as working fluids, a 5% EGD conversion efficiency would be achieved.

KEYWORDS

Electrogasdynamic (EGD), power, ejector and cooling

INTRODUCTION

Electrogasdynamic (EGD) power conversion is accomplished by flowing an electrically charged aerosol against an electric field. The electric charges may be carried by liquid droplets or solid particles. The charged particles suspends in a high speed carrier gas to form a charged aerosol. With the charged aerosol flowing against an electric field, the kinetic energy of working fluids is directly converted to electricity. Compared with conventional turbine generators, there is no moving parts in an EGD converter and so it may be more quiet and reliable. The characteristics of EGD conversion are high voltage and small current. EGD generators have been applied in paint spraying, crop spraying, coating, high voltage supplies for instrumentation and precipitation [1]. The application of EGD for power generation was limited by its low conversion efficiency associated with electric breakdown strength of working fluids [2].

Incorporation of EGD conversion with an ejector cooling system may provide an attractive solution to the shortcoming of EGD conversion. EGD conversion may be carried out in the primary nozzle of an ejector and the remaining kinetic energy of the primary stream of working fluids is used to entrain the vapor of evaporator to cause a cooling effect. This integration system also offers a novel approach for combined cooling and power generation. Compared with other co-generation modes (e.g., turbine, engine, fuel cell, photovoltaic or thermoelectric CHP integrated with absorption or ejection systems) [3-7], the proposed EGD ejector system may be simple and reliable. The studied system may be driven by waste heat or renewable energy. This will make a great contribution to energy saving and reduction in CO_2 emission. The principle of this system will be described and a thermodynamic analysis will be given.

PRINCIPLE

The principle of the EGD power converter is shown schematically in Fig. 1. An EGD converter comprises a corona electrode, an attractor electrode, a collector electrode and a duct of electrically insulation materials. A sufficiently high voltage is imposed between the corona and attractor electrodes to charge the working fluids. When a high pressure vapour (e.g., steam) flows through a converging duct, the expansion causes it to be cooled and part of it to condense. The saturated vapour is electrically charged near the corona electrode to form a charged aerosol. The high speed charged aerosol sweeps itself downstream to release charges at the collector electrode, building up a higher electric potential than the corona electrode. This process is therefore called electrogasdynamic process, in which the kinetic energy of the working fluids is converted to electrical energy. Useful electrical energy is obtained from the converter by connecting a load between the collector and corona electrodes. It can be seen that the direct conversion of heat to power is accomplished in an EGD converter.

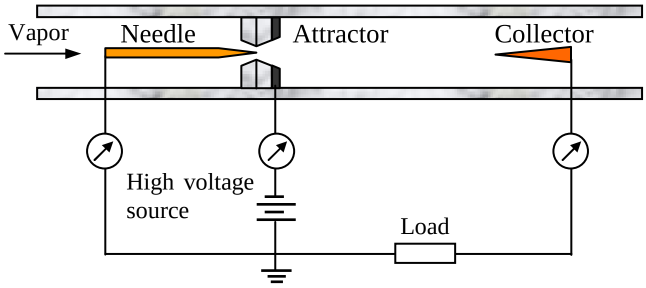


Figure 1 Principle of EGD power converter

An EGD power converter may be integrated into the primary nozzle of the ejector in an ejector cooling system, as shown in Fig. 2. The corona electrode is positioned centrally in the converging section of the nozzle, the annular attractor electrode is placed at the throat and the collector electrode is positioned centrally in the diverging section. The EGD power generation is accomplished in the primary nozzle. The exit vapour of the nozzle continues to entrain the vapour from the evaporator to cause a cooling effect. Therefore, an EGD ejector system may produce combined cooling and electricity. Fig. 3 shows the pressure-enthalpy diagram of the EGD ejector cycle. The EGD conversion process is denoted by process '0-9'.

Energy conservation within the EGD conversion section may be given by:

$$h_0 + \frac{1}{2}u_0^2 = h_9 + \frac{1}{2}u_9^2 + \frac{IV}{\dot{m}_b} \tag{1}$$

where I is the current and V is the voltage produced and the mass flow rate $\dot{m}_b = \rho_0 u_0 A_0$.

The efficiency of EGD power conversion is given by:

$$\eta = \frac{IV}{\dot{m}_b \Delta h_b} \tag{2}$$

The cooling coefficient of performance is:

$$COP = \xi \frac{\Delta h_e}{\Delta h_b} \tag{3}$$

where ξ is the entrainment ratio.

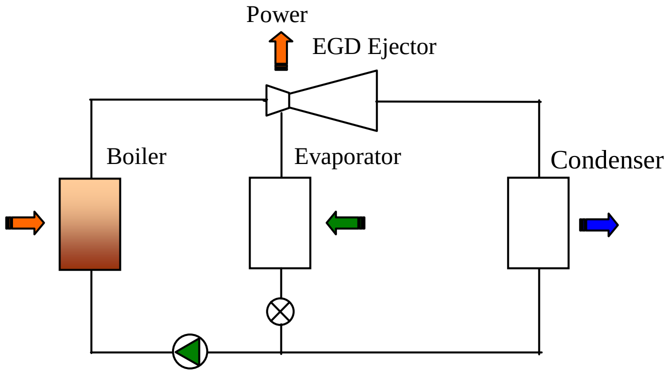


Figure 2 EGD ejection system for combined heating, cooling and power

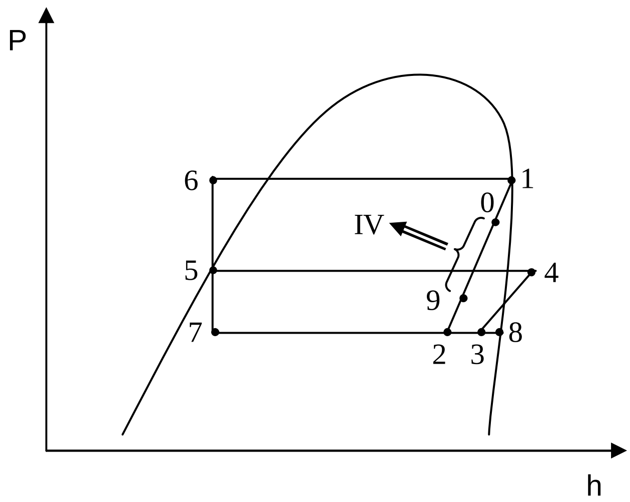


Figure 3 EGD ejection cycle on the Pressure-Enthalpy diagram

Unlike the calculation of common ejector systems, two new parameters, I and V, are introduced. The current I is given in the electrically charging process. So only the voltage V needs to be determined. This may be given by applying the Poisson's equation which correlates the electric potential and the space density of charge:

$$\nabla^2 V = -\frac{\delta}{\varepsilon_0 \varepsilon_r} \tag{4}$$

where the charge density $\delta = I / uA$, ε_0 is the dielectric constant of free space and ε_r is the relative dielectric constant of working fluids.

As a simple example, a constant charge density and one dimension was considered. Integrating eq. (4) and substituting into eq. (2) may give:

$$\eta = \frac{I^2 \rho_0 L^2}{2\dot{m}_b^2 \Delta h_b \varepsilon_0 \varepsilon_r} \tag{5}$$

where L is the length of the EGD conversion section.

ANALYSIS

Eq. (5) shows that the EGD conversion efficiency changes proportionally with the squared current density. This is illustrated in Fig.4. The calculation was done for water as working fluids under 120°C generating temperature, 40°C condensing temperature, 5°C evaporating temperature, 9kW boiler capacity, the nozzle efficiency $\eta_n = 0.90$, the mixing efficiency $\eta_m = 0.80$ and the diffusion efficiency $\eta_d = 0.85$ and the length of conversion section $L = 0.01m$. The left end points represent the case of maximum power conversion in the combined cycle. With the efficiency increasing up to 10.8%, the cooling coefficient of performance comes down from 0.23 to zero. It seems that a power conversion efficiency of up to 10.8% could be achieved in the studied system under the above condition. However, this efficiency will be limited by the electric breakdown strength of working fluids. Along the conversion section the electric field is maximum at the entrance. The calculation showed that for an efficiency of 5% the electric field strength is up to 200kV/mm and even for the efficiency of 1% the electric field strength is still about 100kV/mm. This electric field strength is much bigger than steam electric breakdown strength of 3.22kV/mm under the standard condition. With the limitation of electric breakdown strength, the possible conversion efficiency would be much smaller. If taking into account the electric breakdown strength of working fluids, the possible maximum conversion efficiency may be given by:

$$\eta_b = \frac{\rho_0 B^2 \varepsilon_0 \varepsilon_r}{2\Delta h_b} \qquad (6)$$

where B is the standard electric breakdown strength [2].

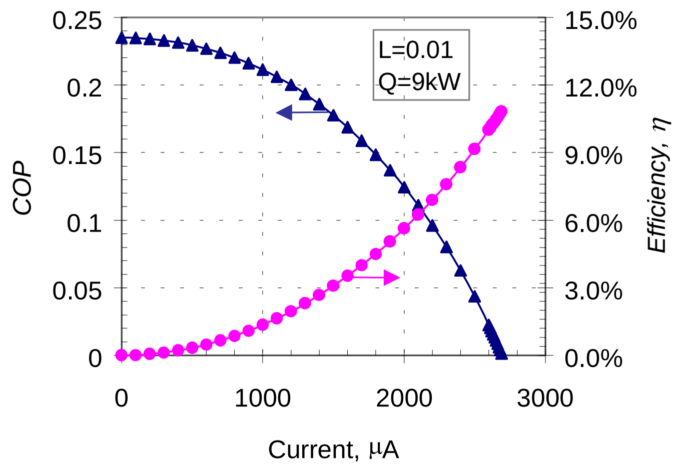
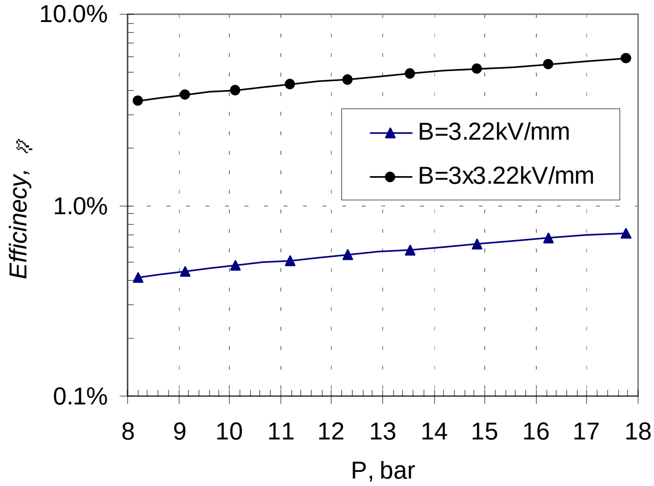


Figure 4 COP and EGD conversion efficiency changes with current (water as working fluids)

It is obvious that the conversion efficiency at electric breakdown increases proportionally with the rise of inlet vapour density and squared standard electric breakdown strength. Steam has B=3.22kV/mm same as air. The conversion efficiency is less than 0.001% for 100~140°C generating temperatures and so there is a very little change in the COP. In order to achieve an efficiency of 5%, the standard electric breakdown strength must be increased by 100 times or the inlet density must be increased by 10000 times. From eq.(6), it is also obvious that a higher efficiency is related to a small specific enthalpy difference of working fluids in vapour generation. These may be achieved by using common refrigerants. For example, for R11 as working fluids, the inlet density can be increased by around 100 times compared with steam and the enthalpy difference can be decreased by about 10 times. This means that for the same standard electric breakdown strength a conversion efficiency of 0.5% may be achieved. If the standard electric breakdown strength can be increased by 3~5 times, a conversion efficiency of around 5% would be achieved. This is illustrated by Fig.5. For R11 as working fluids, a conversion efficiency of 3~6% could be achieved for 100~140^oC generating temperatures if R11 has B=3x3.22 kV/mm. It is true that the halogenated refrigerants have much larger standard electric breakdown strength than air and steam. This will allow a considerable EGD conversion efficiency.

Figure 5 EGD conversion efficiency changes with inlet pressure of the nozzle



(R11 as working fluids)

CONCLUSIONS

Integration of EGD power conversion into ejector cooling systems was presented. This system combines the advantage of simplicity of both EGD conversion and ejector refrigeration. The shortcoming of low efficiency of EGD conversion is overcome because the remaining kinetic energy of working fluids from EGD conversion is used to drive the ejector system. This system may offer a new approach for combined cooling and power generation. The performance of system was analyzed theoretically. The EGD conversion efficiency may be adjusted by changing the operating current and it is also limited by the electric breakdown strength. A high conversion efficiency at electric breakdown may be related to a large inlet density, a high standard electric breakdown strength and a small specific enthalpy difference of generation. A calculation was done for water and R11 as working fluids. The results show that the EGD power conversion efficiency would be less than 0.001% for water due to its small electric breakdown strength. A 5% EGD conversion efficiency may be achieved for R11 as working fluids. The system will be examined experimentally.

Acknowledgements

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Nomenclatures

h specific enthalpy, $kJ \cdot kg^{-1}$

u velocity, $m \cdot s^{-1}$

I curent, A

V voltage, $volt$

$\dot{m}$ mass flow rate, $kg \cdot s^{-1}$

ρ density, $kg \cdot m^{-3}$

η efficiencies of ejector or EGD conversion

ξ entrainment ratio

δ charge density, $C \cdot m^{-3}$

ε_0 dielectric constant of free space, 8.85x10^{-12} $F \cdot m^{-1}$

ε_r relative dielectric constant

L Length of EGD conversion section, m

Δh specific enthalpy difference, $kJ \cdot kg^{-1}$

COP coefficient of performance

Q heat transfer rate, kW

B standard electric breakdown strength, $V \cdot m^{-1}$

subscripts

1,...,9 state points of the cycle
0 state point at the throat of the nozzle
b boiler or breakdown
e evaporator
n nozzle
m mixing
d diffusion

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