PROSPECTS OF THE MAISOTSENKO THERMODYNAMIC CYCLE APPLICATION IN UKRAINE

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The fast growth in organic fuel cost and progressive ambient contamination pushes researchers to search for alternative energy sources. As was recently revealed, the atmospheric air, containing dry gases (O2, N2, others) and water vapor can be considered as an inexhaustible energy source available almost throughout the world. In the adiabatic water-in-air evaporation the latent heat is extracted from air providing the air enthalpy reduction. The nonequilibrium in form of the temperature difference between wet ambient air and air making contact with evaporated water (psychrometric temperature difference, or temperature difference between dry and wet bulb temperatures) can be used as an energy source. Before investigations of American scientist Professor Valeriy Maisotsenko (former citizen of Ukraine), due to a little magnitude, the psychrometric temperature difference was not applied in practice. He was the first researcher who paid attention to how the psychrometric temperature difference can be used in various applications. This paper considers potential applications of M-Cycle in Ukraine in power and heat-and-mass transfer technologies.

KEY WORDS: indirect evaporative cooling, dew point, wet bulb, psychrometric chart, humidification, gas turbine

1. INTRODUCTION

A high psychometric temperature difference can be created in the counter-flow (or cross-flow) indirect evaporative cooling heat and mass exchanger with a number of small-sized wet and dry channels. In such equipment the heat and mass transfer
processes are close to invertible ones enabling to reach the maximum air (gas) cooling at minimum losses. As the thermodynamic performance rate is close to unity, then the dew point temperature is the theoretical limit of an air (gas) cooling in the indirect evaporative cooling. Note that in the direct evaporative cooling only the wet bulb temperature of the cooled air (gas) can be achieved. When the sequence of direct cooling devices is used, the cooling effect might be close to the dew point temperature; however, the equipment cost goes up dramatically.

Based on the thermodynamics of wet flow, Professor Valeriy Maisotsenko (USA) has developed and patented in many countries the new thermodynamic cycle, currently known as Maisotsenko Cycle, or M-Cycle. This cycle has paved the way for obtaining the higher psychometric temperature difference and its utilization in various energy, heat, and mass transfer technologies (Idalex, 2010a,b; Gillan, 2008; Wickler, 2003; Chandracant, 2012; Maisotsenko and Reizin, 2005). Based on the M-Cycle, a few novel energy-efficient and cost-effective renewable and conventional energy technologies have been developed by Maisotsenko and his colleagues (Idalex, 2010a,b; Maisotsenko et al., 2010).

The representative cell of a counter-flow evaporative heat and mass exchanger with two independent air flows is presented in Fig. 1a (Idalex, 2010a). The working air enters the working dry channel \( t_{\text{WB}} = 86^\circ F \); Fig. 1b], where it cools down due to contact with the wet working channel back side, in which the water is evaporated. Ideally, at the wet channel inlet this air reaches the inlet air dew point temperature \( t_{\text{DP}} = 54.7^\circ F \) [in real conditions, point 2, \( t = 55.6^\circ F \); Fig. 1b]. Due to the water in wet channel evaporation the temperature of air contacting both channel walls drops down (effect of the latent evaporation heat). Here the air is saturated; therefore at the channel exit its temperature drops down close to the wet bulb temperature [point 3; Fig. 1b].
As both wet channel walls are cooled down, this is used to reduce the air temperature in the product channel from atmospheric flow conditions [point 1; Fig. 1b] close to the dew point temperature of the incoming air [point 2; Fig. 1b]. Thus, the air flow in both dry channels is cooled down due to the water evaporation in the working wet channel, where the driving force of heat and mass transfer is the psychrometric temperature difference. Within the web channel the air humidity increases, while the air temperature (enthalpy) goes up. As far as the direct cooling is concerned the cooling effect is only 20°F from 86°F to 66°F (Fig. 1b).

Figure 2 represents a more detailed analysis of a psychrometric chart of the M-Cycle. The line 1–3–4–1 demonstrates the ideal Maisotsenko cycle (Idalex, 2010a), where the line 1–3 is the air cooling in the working dry channel, 3–4 is the air heating and saturation in the working wet channel, 4–1 is the return to the cycle starting point. At the air inlet temperature of 160°F the absolute air humidity elevates from 0.025 to 0.53 kg/kg, e.g., more than 20 times. The wet air enthalpy growth is determined by the enthalpy difference in p. 3 and 4, while the temperature reduction in the product channel is determined by the temperature difference in p. 6 and 5. Thus, the M-Cycle utilizes the enthalpy difference between air at the dew point temperature and the same air saturated at a higher temperature. This enthalpy difference is used to efficiently reject the heat from the air in the dry working channel and product channel through the water latent evaporation heat.
As follows from Fig. 2 the air cooling effect in M-Cycle is 81.9°F (from 160°F to 78.1°F), while at the conventional (direct) cooling this effect (line 1–7) is only 43°F (from 160°F to 117°F). As seen from Fig. 2, the greater the inlet air temperature, the more cooling effect can be achieved in the product channel. It is the primary M-Cycle advantage, as its efficiency grows when the air temperature increases. In the refrigeration the inverse effect occurs and the efficiency of the Ranque cycle drops down. Also, the dryer the inlet air, the greater the cooling effect can be obtained; therefore the incoming air drying can be employed to elevate the M-Cycle efficiency in the world zones with high air humidity (Gillan, 2008).

In actual conditions the line 1–2 represents the air cooling in the working dry channel, while the line 2–3′–8 describes the air heating and humidification in the working wet channel. The conventional (direct) cooling is characterized by the line 6–7 (ideal process) and line 6–9 (real process). Thus, the air humidity attained in the M-Cycle is 6.5 times greater than the humidity rate achieved in the direct cooling system (0.025–0.08 kg/kg; Fig. 2), where the air humidity grows only 3.2 times. More than four times growth in the wet air enthalpy throughout the M-Cycle (constant enthalpy lines are not shown in Fig. 2) brings great opportunity in various industrial applications.

As found, at the identical inlet parameters the thermodynamic performance rate of the counter-flow indirect evaporative cooling scheme is 2.5 times greater than the traditional direct cooling. The energy effectiveness of such equipment (the cold production to the energy required for air transport) is substantially greater than the refrigeration coefficient of the traditional refrigeration plant. The experimental studies have confirmed that the air temperature at the working dry channel exit is below the wet bulb temperature and approaches 80% of its dew point temperature. The working channel air temperature is very near its saturation point or inlet dry bulb temperature.

To provide uniform wetting of the wet channel surfaces with no local water excess, cellulose material with low thermal resistance through its thickness is usually used, acting as a capillary wick. Note that quite a small amount of water is needed to soak the wet surface. As far as the water entering temperature is concerned, it has a small effect on the product air temperature, as the latent water evaporation heat plays the primary role in heat and mass transfer process.

The primary advantages of the equipment based on the M-Cycle are (i) ecological safety, (ii) energy efficiency, (iii) competitive capital cost, (iv) lower operational and maintenance cost, and (v) relatively simple design. As all heat and mass transfer processes happen at atmospheric conditions, the water leakage problem is not a design problem. The most important advantage is that a compressor and refrigerant are not used in the M-Cycle equipment.

When using the M-Cycle, the high air cooling effect can be achieved in many world climatic zones, except the tropics and subtropics zones. Some climatic conditions of the selected European cities are given below (Zhan et al., 2011): Copenhagen (Denmark): Wet bulb temperature (WB) is 17.3°C, Dew point temperature 144
(DP) is 13.5°C; London (UK): WB = 20°C, DP = 14.6°C; Catania (Italy): WB = 21.6°C, DP = 16.2°C; Izmir (Turkey): WB = 20.4°C, DP = 12.5°C; Kiev (Ukraine): WB = 16.1°C, DP = 9.2°C (August, 2012). Despite quite a little difference between these temperatures, it shows remarkable potential in various industrial applications.

The representative cell, presented in Fig. 1, is the basis not only of air cooling systems (conditioners), but also of many power and heat and mass transfer devices. In all cases the atmospheric air (any gas) comes through the dry and wet working channel. As far as the dry product channel is concerned, the discharged hot gas is coming through this channel in power systems, while in heat and mass transfer devices it is any cooled medium.

As only the atmospheric air energy is used in the M-Cycle equipment, the energy cost produced is therefore lower compared to all other renewable energy technologies.

2. PROSPECTS OF M-CYCLE APPLICATIONS IN UKRAINE

The potential applications of M-Cycle cover a number of energy and heat and mass transfer technologies (Idalex, 2010a,b; Chandracant, 2012; Maisotsenko and Reizin, 2005). Currently this cycle is applied in the evaporative, hybrid, and solar conditioners, and solar photovoltaic (PV) panel cooling systems. The pilot projects, which are now under development, include the cooling towers, gas turbine inlet air cooling systems, distillation and desalination systems, and humidifying air recuperators.

The first time the M-Cycle technology was proven and realized was in a new generation of air conditioners (Coolerado Company, Denver, CO, USA). Currently they are produced in the USA, Europe, India, Australia, South America, China, and Singapore. As proven by the National Renewable Energy Lab (NREL, USA) the M-Cycle conditioners are 10 times more efficient than traditional air cooling systems of the compression type (NREL, 2003). Moreover, the M-Cycle conditioners use 100% clean ambient air, while traditional conditioners use 85% recirculating (already used) air. The calculations have shown the maximum (19.14%) and minimum (8.45%) exergy efficiencies of the M-Cycle can be obtained for atmospheric air temperatures of 23.88°C and 10°C, respectively (Galliskan et al., 2011).

Countries with a large number of sunny days can receive solar conditioners using counter-flow indirect evaporative cooler, supplied with an atmospheric air fan operating from the PV panel of a small power. For example, the solar conditioner Coolerado Cooler R600, based on three 200 Wt, power PV panels, supplying electricity to the M-Cycle equipment is able to cool a room 225 m². For this purpose the traditional conditioner systems require 20–30 PV panels or 4–6 kWt power. The wide application in Ukraine is in hybrid conditioners combining traditional compression conditioners with counter-flow indirect evaporative cooling equipment. This allows an 80% reduction in the electricity consumption used by traditional conditioners. The cooling of solar PV panels by means of M-Cycle
equipment is also used in solar conditioners of the Coolerado Co. (USA), providing increases in the efficiency of such a plant from 12–15% to 30–32%.

In the near future M-Cycle will find wide applications in internal combustion engines, power gas turbine engineering, water heaters, water distillation systems, fuel burners, water condensers, industrial furnaces, and thermochemical recuperation systems.

For example, a ceramic heat and mass exchanger, installed at the car exit, where the outlet temperature is 540–980°C, allows utilizing of the heat and water vapor from outgoing gases, as well as the heat from the engine cooling system. This, in the future, can exclude the external water cooler (radiator) from the engine cooling system. Reduction in the low thermodynamic cycle temperature (below the wet bulb temperature) and effective heat utilization system will be able to elevate the efficiency of the internal combustion engine from 30% to 55–60%. The official testing, carried out by the University of California Davis Center (USA), has shown that liquid fuel burning in a highly wetted air (30–40% humidity) leads to a significant decrease in NO\textsubscript{x} level, discharged into the ambient.

Quite often, the limiting factor in various industrial applications is the water temperature cooled in the cooling towers (Gas Technology Institute, 2012; www.gastechnology.org). The colder the water, the more enhanced the vapor condensation is that occurs in condensers, which is widely applied in power and chemical engineering. In the power station, poor vacuum due to insufficient water temperature in the condenser yielded a drop in thermal efficiency and an increase in fuel consumption. The survey carried out by the Electric Power Research Institute (EPRI, USA) has shown that 65% of cooling towers in the USA were performing at 80% of their capability. This deficiency was costing the U.S. electric generating industry over $100,000,000 per year in added power (Burger, 2000).

Currently over one million cooling towers are exploited around the world; among those about 50% are installed in the USA. In theory, if the ambient air temperature is 32°C and the relative air humidity is 35%, the cooled water temperature in such devices can be reduced by 10°C, e.g., from 32°C to 22°C. However, typically, traditional cooling towers provide 65–70% efficiency, or a 6–7°C temperature drop. As the cold water temperature produced in such a tower is limited to the ambient air wet bulb temperature, the traditional cooling tower technology is mostly suitable in very dry regions. Nevertheless, many traditional cooling towers exploited in the Ukraine operate in regions where the air moisture varies from 30% to 40%. As a result, their operation efficiency is not optimal. The film-type packing is able to expose greater air-water contact surface within a given volume. However, even in this case the water can be cooled down to near the wet bulb temperature.

At the ambient air temperature of 30°C and its relative humidity of 35%, the cooled water temperature in the traditional cooling tower of the 500 MWt power station using the Ranque cycle reduces from 38°C to 24°C (Maisotsenko et al., 2010; Gillan et al., 2011). If the M-Cycle is used with minor design changes (Fig. 3c) the outlet
water temperature can be reduced to 13°C. Due to this effect the water mass flow rate coming through an M-Cycle cooling tower reduces by 44%, while the makeup water flow rate reduces by 20%. As a whole, in regions with low and moderate air humidity (20–40%) application of the M-Cycle leads to a reduction in the water flow rate through the cooling tower by 47–33%. At an air humidity of 60% and over, this flow rate is identical for the traditional cooling tower and the cooling tower based on the M-Cycle. Note that in the very near future the water supply will become the burning problem of nuclear and thermal power engineering in

FIG. 3: M-Cycle in open cooling tower; M-Cycle flow scheme (a), psychrometric chart (b), the fill according to traditional and M-Cycle cooling tower (c) (Maisotsenko et al., 2010; Gillan et al., 2011; Glanville and Kozlov, 2010)
Ukraine, where high-capacity steam turbines are widely employed. At the same time, the fresh water resources in Ukraine are very limited.

Overall, about 44% of 300 MWt\textsubscript{e} coal power stations are now in operation in Ukraine. The additional 11°C water temperature cooling in the M-Cycle cooling tower compared to the traditional cooling tower allows for the thermal power station of 300 MWt power to save over $400,000 annually due to efficiency growth and associated fuel reduction. In the scale of the Ukraine application of M-Cycle cooling tower it saves over $25,000,000 per year. The water mass flow rate coming through the M-Cycle cooling tower is getting lower by 25–30%, promoting remarkable efficiency growth of 300 MWt thermal power stations. If only the electricity production growth is taken into consideration (electricity sales price is $0.036), then the additional gain of $500,000 per year can be earned for the same power station. In the scale of the Ukraine application of the M-Cycle cooling tower for 200 and 300 MWt\textsubscript{e} coal power stations this provides great profit including $25,000,000 annually.

Application of the M-Cycle in cooling towers is not limited by using the atmospheric air as the working medium. The nitrogen, carbon dioxide, various industrial gases, waste water, sea water, and other liquids can be employed in various industrial cooling towers.

In the M-Cycle cooling tower modernization the body of the traditional cooling tower (80% of the cost) is retained, but only the fill and air supply into the fill is changed. The tower fill costs around $100 per 1 m\textsuperscript{3} (or $150,000–$200,000 for a power station of 300 MWt\textsubscript{e} power), while modernization of the air supply and other expenses include around $100,000. Taking into consideration the saving of $400,000 due to deeper water cooling in the M-Cycle cooling power of a 300 MWt\textsubscript{e} power station, it is possible to conclude that all investments can be returned within one year or less.

Application of the M-Cycle cooling tower will bring great economic advantages to other industries of Ukraine. For example, a reduction in 1.7°C water temperature (from 25.6°C to 23.9°C) in monophosphate production results in an extra 12 tons per hour of production (Burger, 2000). For every 1 of colder water used for the compressor cooling, there is a 4.5% reduction in electric energy required to power the equipment. The large chemical plant can lose over $25,000,000 per year due to a reduction in the product capacity, if the exit cooling tower temperature is only 3°C lower against design conditions (Burger, 2000).

The exergetic tower (Fig. 4) represents great interest in renewable energy systems for the production of electricity, cooled air, and cooled water (Maisotsenko et al., 2010). It includes two vertical co-centric cylinders, in which the water is evaporated from the external surface of the internal cylinder. The start of heat and mass transfer processes provides a forced air supply into the inner cylinder and further water evaporation from the external wall of the internal cylinder. According to Fig. 2 data, in the central tower channel, where the air stream moves down, its temperature decreases, while in the annular gap air moves upwards with air humid-
ity and temperature increase. As a result, the exit mass flow rate is much greater than that supplied at the inlet. This differs substantially the exergetic tower design from other energetic towers of a great height, which have identical mass flow rates in both channels.

The M-Cycle exergetic tower is not limited to ambient air application. Various gases, such as the nitrogen, industrial gases, waste water, and carbon dioxide can also be used to cool down any liquid (industrial, waste). According to Fig. 2, the air/water lowest (dew point) temperature is achieved in the exergetic tower bottom. The wind-power system installed in the exergetic tower bottom (Fig. 4) may produce the electricity. At the same time the cold air and cooled water (both taken from the bottom) can be produced for various applications.

The operating efficiency of M-Cycle exergetic tower can be increased by various methods, including solar heating from the outside, inlet air dehumidification (re-generative desiccant system), and incoming air (gas) preheating. An exergetic tower 10 m in height is able to generate up to 25 kWt hours electricity per day. Therefore, any industrial tube supplied with the M-Cycle device may be employed for energy, cold air, and cooled water production. In some cases the closed-type cooling tower can also be employed, providing the same operational parameters.

There is great interest in Ukraine in waste and salt water distillation devices to produce fresh water, as well as water production from surrounding ambient. In this case the hot air is supplied into the working dry channel (Fig. 1a), passes through the working wet channel, where it cools down due to water evaporation, and then
is supplied partly into the dry cooling channel to initiate the water condensation due to cooling. As found, the operating cost per 1000 gallons of recycled water is $0.91 with 90–95% obtained in the system (Maisotsenko et al., 2010). This is much cheaper than the reverse osmosis technology ($2.91) widely employed throughout the world.

In Ukraine the M-Cycle can find applications in many other energy saving technologies. Among these are waste heat utilization systems (industrial gases, conditioners, ventilation), burners using high humidity air (up to 30%) to reduce NOx emission, and condensers of heat pumps. The M-Cycle has great potential in powerful electronic cooling, where a huge amount of heat is rejected from the relatively small surface (Maisotsenko and Reizin, 2005).

3. M-CYCLE IN GAS TURBINE INDUSTRY OF UKRAINE

Gas turbines are widely used in energy and power engineering, aviation, shipbuilding, and mechanical driving systems. Today up to 70% of new electricity generating plants in the world are based on the simple cycle (SC) and combined heat and power (CHP) gas turbines. Around 20% of the world’s electricity is now produced using SC and CHP gas turbine systems. As planned, by 2020 over 20% of the total electricity will be generated in the USA by means of SC and CHP gas turbines. In the leading countries almost 30% of the peak and half-peak load is provided by gas turbine systems. In Ukraine over 450 gas turbines (4500 MWt power) are employed for mechanical driving of natural gas pumps in the national pipelines. As planned, an 800 MWt combined heat and power station, based on two gas turbines with 240–260 MWt power, and one steam turbine will be installed in Ukraine (Crimea Peninsula) in the very near future.

Despite quite high perfection, the efficiency of modern power gas turbines does not exceed 40%, so far (SGT5-800H; 375 MWt; Siemens, Germany). To increase the efficiency various methods are now in use, the primary being the inlet temperature growth and the air pressure ratio elevation in the compressor. The major problem associated with development of powerful gas turbines is design and production of an axial compressor with high mass flow rate (up to 800 kg/s). Very effective complex thermodynamic cycles include the combined heat and power cycle, exit heat regeneration, interstage air cooling in compressor, interstage flow heating in gas turbine, water steam injection into a combustion chamber, and gas turbine. Today, the most powerful in the world is the CHP gas turbine SGT5-800H (570 MWt) providing the efficiency of 60%. Overall, around 7 years and over 550 euros were spent in this program.

The Ukraine is one of ten world-leading countries providing the full cycle of design and series production of gas turbines for aviation, marine application, energy and power systems, and mechanical driving (up to 25 MWt power). The Gas Turbine Research and Production Complex Zorya-Mashproekt (Nikolaev City) is one
of the world leaders in the marine gas turbine market; also this complex has for over 50 years produced in series gas turbines with power from 2.5 to 25 MWt for energy and power systems, and mechanical driving of natural gas pumps and compressors. For power engineering a 110 MWt gas turbine with the efficiency of 52% has been developed and tested in Russia. Recently the test stage was started for a gas turbine with 45/60 MWt power designed for power systems. The aviation gas turbine engines of design company Ivchenko-Progress (Zaporozh’e City) are used in many countries of the world; over 800 of their gas turbine pumping systems are used in pipelines of the former USSR (NPO Frunze; Sumi City). The enterprise Turboatom (Kharkov City) has developed powerful gas and steam turbines for power and nuclear stations.

Over the last 30 years the Gas Turbine Research and Production Complex Zorya-Mashproekt (Ukraine) gained vast experience in the design of gas turbines using the complex thermodynamic cycle. Among those the CHP gas turbines with 13.5–25 MWt_e power (efficiency is 45.8–48.5%) and gas turbines based on STIG technology (4.3–40 MWt_e; efficiency is 35.5–42.8%) can be mentioned. Based on the gas turbine 10 MWt_i power, the gas turbine system Vodoley-16K (Aquarius-16K) has been developed and tested as the electric generator drive (16 MWt_e) in Gas Turbine Research and Production Complex Zorya-Mashproekt (Zorya-Mashproekt Product Catalog, 2009). In 1993 the mechanical drive gas turbine system Vodoley-16K (16 MWt power, efficiency is 42.1%) was introduced into experimental and commercial operation at the Stavishcenskaya Compressor Station of the Kiev region (Ukraine).

The contact heat and mass exchanger installed after the Vodoley-16K system provides the heat and water utilization from combustion gases, including the water formed at the natural gas burning. Results of testing have shown that the exit flow temperature is 43–45°C; moreover, the water return coefficient is more than unity up to the ambient air temperature of 25°C. As calculations show, the efficiency of the Vodoley gas turbine system can be around 50%, if the flow temperature in front of the gas turbine is 1350–1400°C.

All gas turbine cycles based on air humidification (STIG, HAT, CHAT) provide high operational efficiency; however, they have very complex infrastructure. The major limitation of the HAT (humid air turbine) cycle is the humidification process, which uses a column providing evaporation to the water boiling temperature at a high air compressed air. Raising humidity beyond this point requires a separate boiler whose cost, maintenance, pressure, and heat losses are significant. The other important problem is the number of heat exchangers and expensive purified water equipment. As the water steam discharges into the ambient after operation, the high air moisture causes ecological problems for adjacent territories and people living in the area.

The air humidity rate attained in these cycles is around 15–20%, while the theoretical limit of outgoing gas temperature is the wet bulb temperature. As shown
above, in M-Cycle very high humidity (up to 30%) is attained in a single device; this equipment is cost effective, as it provides a high rate of heat and mass transfer augmentation. After operation the water is utilized in the exit heat and mass transfer equipment to be used again in the cycle.

The scheme of a gas turbine plant, based on the M-Cycle, is given in Fig. 5. Application of two independent counter-flow indirect evaporative heat and mass exchangers enables one to solve a few design and thermodynamic problems. Firstly, the "low" cycle temperature reduces to near the dew point temperature, thus elevating the gas turbine efficiency. At the same time, the exit heat and water from the cycle and combustion gases is utilized. Secondly, the higher humidity compressed air (up to 30%) in front of the combustion chamber may be obtained in a single device. Introduction of the high humidity air into the combustion chamber increases the gas turbine power and remarkably reduces the rate of harmful products discharged into the atmosphere (Soroka, 1993). Thirdly, application of an inlet M-Cycle cooling device provides inlet air cooling in summer time without an air humidification that is typical for all other cooling technologies. Experiments have shown that pressure losses in the exit heat and mass exchanger have a weak influence on the gas turbine efficiency. If two exit heat and mass exchangers are used in a design that is stipulated by operation conditions, then the thermal efficiency reduces by 2–3%.

As follows from gas turbine theory, when the ambient air temperature is over +15°C, reduction in the air inlet temperature by 1.0°C leads to an increase in the

**FIG. 5:** The M-Cycle gas turbine with air cooling in front of compressor (Gillan and Maisotsenko, 2003)
gas turbine efficiency by 0.5–0.7%. The colder the air, the higher its density that provides a greater air mass flow rate and compression ratio. The water used for the inlet air cooling is utilized and then is returned into the cycle via a regeneration system. Also, the wet discharged air can be utilized in the interstage compressor cooling system, thus increasing the gas turbine efficiency.

The M-Cycle can effectively be employed in gas turbines of different sizes—from micro-turbines up to powerful gas turbines. The important advantage of this cycle is that high gas turbine efficiency is maintained even at partial gas turbine loads up to 50%. Compared with a CHP gas turbine the high efficiency of 60% is reached in the M-Cycle gas turbine without steam turbine, condenser, and other bulk and expensive equipment.

Investigations of the M-Cycle gas turbine are in the initial stage, so far. Nevertheless, even the first results available have shown clear M-Cycle advantages over the well known HAT cycle. In the M-Cycle gas turbine the cooling of combustion products is to near the dew point temperature; therefore, the efficiency grows due to the lower cycle temperature. As told above, application of high humidity air improves the fuel combustion process and reduces nitrogen oxide formation. According to Soroka (1993), when the air moisture grows from 3% to 39%, the nitrogen oxide concentration drops by 13.5 times. This is due to the higher wet air heat capacity and more uniform temperature field in the combustion chamber without "sharp" temperature peaks. In addition, small water steam dissociation and the hydrogen and oxygen formation in the combustion chamber enhances the combustion process.

The theoretical thermal efficiency of the Maisotsenko cycle can be written as (Maisotsenko et al., 2010)

\[ \eta_M = 1 - \left[ \frac{(t_{\text{out,M}} - t_{\text{amb}})}{(t_{\text{out,B}} - t_{\text{amb}})} \right] \left( 1 - \eta_B \right) \left( \frac{m_2}{m_1} \right), \]

where \( t_{\text{out,M}} \), \( t_{\text{out,B}} \) is the outgoing flow temperature according to the Maisotsenko and Brayton cycle; \( \eta_B \) is the actual thermal efficiency of the Brayton cycle; \( m_2 \), \( m_1 \) is mass flow rate through the gas turbine according to the Maisotsenko and Brayton cycle.

As an example, the stationary gas turbine UGT-25 (25 MWt, production of Gas Turbine Research and Production Complex Zorya-Mashproekt, Ukraine) is analyzed below. The inlet air temperature is 1350°C, outgoing gas temperature is 465°C, the ideal Brayton cycle thermal efficiency is 0.48 (Carnot cycle efficiency is 0.82), and gas turbine actual thermal efficiency is 0.37. In the M-Cycle gas turbine the \( m_2 / m_1 \) ratio ranges from 1.1 to 1.2 (Maisotsenko et al.; 2010); therefore assume \( m_2 / m_1 = 1.2 \). From the correlation (1) for the ambient air temperature \( t_{\text{amb}} \) of 27°C the following equation can be obtained: \( M = 1 - 1.92 \times 10^{-3} (t_{\text{out,M}} - 27^\circ C) \).

Due to the higher flow humidity, the exhaust gas dew point temperature is approximately 80–120°C that is greater than the ambient air dew point temperature.
Therefore, it is possible to assume that water condensation from combustion gases starts at 80–120°C that is the M-Cycle outlet temperature $t_{\text{out,M}}$. Then for $t_{\text{out,M}}$ of 100°C and $t_{\text{out,M}} - t_{\text{amb}} = 73°C$, $\eta_M \approx 86\%$ can be obtained, e.g., around 86% of the fuel chemical energy can be used in M-Cycle gas turbine. It is greater than in the ideal Brayton cycle and even higher than in the Carnot cycle.

The greater M-Cycle thermal efficiency compared to the Carnot cycle can be explained by a fundamental difference between these cycles. The Carnot cycle is based on the single working medium, coming through compression-external heating (combustion)-expansion to the dry bulb (ambient) temperature. The M-Cycle employs two different working mediums with different flow rates, namely compressed air and wet combustion products. Ideally, in M-Cycle expansion of wet combustion products are provided to the dew point temperature that substantially reduce the "low" thermodynamic cycle temperature.

Application of two different working mediums brings some other advantages. As the moisture is added to air after the compressor, so to keep the same mass flow rate as for the basic engine, a smaller air amount can be compressed in the compressor. Thus, the compressor power is reduced compared to the basic engine of the same power. At the same mass flow rate the blend "wet steam-combustion products" has a lower density to be characterized by a greater expansion rate. As a result, the volume flow rate of the working medium coming through the gas turbine increases and elevates its power.

The Ukraine gained vast experience in design of the complex thermodynamic cycle gas turbines (STIG and Vodoley cycles), and has a good opportunity to become a world leader in using the M-Cycle in the design of the next generation of gas turbines. As a first step the micro-turbine systems can be employed to prove the M-Cycle.

In 2005 the Department of Water and Power of the City of Los Angeles, CA (USA) Distribution Power Unit along with Coolerado Corporation (Denver, CO, USA) carried out the Capstone C30 micro-turbine testing. These experiments have shown that application of the M-Cycle inlet air cooling device have provided a temperature reduction of 8°C from 32°C to 24°C. In the maximum power mode the growth of power attained was 8.8%, while in the maximum efficiency mode the power increase was 11.7%. As far as the thermal efficiency is concerned, in the first case this index has increased by 3.4%, while in the second one it increased by 0.2%.

To provide the M-Cycle testing in actual conditions the Vodoley-16K gas turbine system can be used as currently used in the Ukrainian pipeline, having all infrastructures required. For the modernization of Vodoley-16K two separate indirect evaporative cooling heat and mass exchangers should be installed, namely at the compressor inlet and beyond the gas turbine (Fig. 5). Due to the inlet air cooling in summer time the gas turbine efficiency can be increased by 10–12%. In the scale of Ukrainian pipeline it saves around 900,000,000 m$^3$ of natural gas annually, the cost of which is over $400,000,000.
A very important stage of such a project is an extensive thermodynamic and cost-effective analysis of the modified Vodoley-16K system and assessment of high humidity air application. The independent interest is application of the M-Cycle in the water purification system (around 800 tons of the chemically purified water is used in the cycle), as well as in the water regeneration system using wet air discharged into the atmosphere.

The M-Cycle can effectively be employed in the design of complex cycle gas turbines. Recently the Gas Turbine Research and Production Complex Zorya-Mashproekt (Ukraine) developed the project of a 16 MWt gas turbine for the Ukrainian pipeline. Application of exit air-to-air heat exchanger is able to reach the gas turbine efficiency of 40% with 980°C of the inlet flow temperature. If the M-Cycle heat and mass exchanger is used in this project, the gas turbine efficiency might be increased to 50–55%.

The cooling of natural gas after pumping is the burning problem of the Ukrainian pipeline network (over 80 compressor stations are in the country). Currently, to cool the compressed air after pumping, obsolete and bulky equipment is used, consuming a lot of electricity. The cost of the single unit of such equipment is over $30,000, moreover 12–14 units are installed within each compressor station. On average, one compressor station uses about 300 kWt of electric power to drive fans supplying atmospheric air to cool the compressed natural gas to 45°C in heat exchangers. During the whole year (6000 operation hours) on average one compressor station pays about $250,000 for electricity consumption. The reasonable solution of this problem can bring significant financial savings in the scale of Ukraine. In particular, the M-Cycle technology can be employed for this purpose with the term of investment of about 1–2 years.

4. SCIENTIFIC COOPERATION

Application of the M-Cycle in various industries requires additional studies in the thermal physics, fuel combustion, gas turbine theory, and material sciences. These investigations can be carried out in institutions of the National Academy of Sciences of Ukraine. Also, the scientific support from the Academy will be required during the design stage and pilot testing of M-Cycle devices.

Presently, fundamental and applied studies of the M-Cycle are actively carried out in the countries of Europe, Asia, Australia, and South and North America. In particular, in the USA intense research is being done at GTI (Gas Technology Institute, Chicago) and Idalex Corporation (Denver, CO) in association with universities, research institutes, and industrial companies of USA, Europe, and other countries.

In 2011 the agreement on the scientific and engineering cooperation between the National Academy of Sciences of Ukraine (Division of Physical and Engineering Problems of Energetic, DPEPE NASU), Gas Technology Institute, and Idalex Corporation (both USA) was signed including fundamental studies of M-Cycle and various industrial applications. In particular, the institutes of DPEPE NASU are in-
interested in developing M-Cycle cooling towers, cooling devices of compressed natural gas in the Ukrainian pipeline, refrigeration and gas turbine systems, water desalination equipment, and burners using the high moisture air. As planned, Gas Turbine Research and Production Complex Zorya-Mashproekt (Nikolaev City, Ukraine), which has gained over 50 years experience, will be in charge of gas turbine projects.

5. CONCLUSIONS

The novel thermodynamic M-Cycle provides a wide opportunity to improve a number of power and heat and mass transfer devices without external work. To cool air (gas) toward near the dew point temperature quite simple equipment is used, based on the unique Maisotsenko heat and mass exchanger. As far as Ukraine is concerned, the M-Cycle can find broad applications in conditioners, industrial cooling towers, solar and wind plants, gas turbine and chemical engineering, heat pumps, condensers, electronic cooling, and industrial water treatment. Devices of the M-Cycle demonstrate the high operation parameters that are cost effective and have less harmful influence on the ambient.

Application of the M-Cycle in gas turbine engineering provides greater cycle temperature difference, increase in thermal efficiency without inlet temperature growth, less nitrogen dioxide formation, reduced axial compressor load, and greater turbine power. Full water return, including that from combustion gases provides no water loss in the cycle. This recovered water is then used in the M-Cycle devices. The cooling of inlet air temperature is effectively used to elevate the gas turbine efficiency, as well as to provide gas turbine power variations without efficiency loss when covering both peak and partial-peak loading.

As a first stage, to assess advantages and drawbacks of M-Cycle gas turbines in more detail, the pilot project of a micro-turbine 30 MWt electric power can be performed in Ukraine. At the second stage a more powerful Ukrainian gas turbine, Vodoley-16K (16 MWt power), might be employed, which has been in operation since 1993 in the Ukrainian pipeline network. The experienced Ukrainian enterprise Zorya-Mashproekt could be in charge of the advanced gas turbine projects, while scientific support would be provided by research institutes of the National Academy of Sciences of Ukraine. Also, the leading organizations of USA and Europe should be attracted to these projects.

As a whole, a wide application of M-Cycle in various industries of Ukraine would provide solid ground to develop a new energy-saving strategy in Ukraine.

REFERENCES


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