An evaluation of humidified discharge cycle for cryogenic pumped heat energy storage

1st Ana Borissova
Department of Thermal and Nuclear Power Engineering
Technical University of Sofia
Sofia, Bulgaria
anborisova@tu-sofia.bg

2nd Kaloyan Hristov
Department of Thermal and Nuclear Power Engineering
Technical University of Sofia
(of Affiliation)
Sofia, Bulgaria
k.hristov@tu-sofia.bg

3rd Dimityr Popov
Department of Thermal and Nuclear Power Engineering)
Technical University of Sofia
(of Affiliation)
Sofia, Bulgaria
dpopov@tu-sofia.bg

***Abstract*—Liquid air energy storage as a standalone technology cannot compete with more mature energy storage solutions. After proving that air humidification improves the round-trip efficiency of the system, the next logical step is to try to utilize any excess heat and investigate ways incorporate it in existing and new installations. The present research focuses on central heating plants combined with humidified discharge cycle and the achieved results show an increase in round-trip efficiency from 59% to nearly 71%.**

***Keywords*—liquid air, energy storage, air humidification, roundtrip efficiency, central heating**

I. Introduction

Finding new ways to further improve existing technologies for energy production and storage is becoming a staple first step for not only achieving the ambitious European sustainability goals but also exceling in utilizing every bit of excess and consequently lost energy flow.

Detecting the potential processes that lack adequate parameters' optimization is a vast task that requires delving deeper into systems that might be deemed not suitable or practical for commercial implementation.

Cryogenic energy storage despite its current limitations is theoretically proven way to deal with electricity production/consumption imbalances. Combining the technology with liquid air energy storage (LAES) might be a potential balancing solution.

The practical applications of LAES are currently not commercially applicable. Not only do these systems introduce a great degree of complexity, but their round-trip efficiency (RTE) cannot compete with mature accumulation strategies.

Many recent studies in this field have shown that the main cause for low round-trip efficiency is the discharge process's inability to efficiently use stored compression heat. Our previous work [1] concentrated on summarizing and analyzing the predeceasing studies on the subject. What is worth mentioning is the significant amount of lost compression heat – up to 45%. Some researchers propose the introduction of organic Rankine cycle to the system, tri-generation or constructing an installation capable of maintaining the whole energy consumption of a building.

In our preceding research [1], we put forth the concept of a humidified discharge cycle, wherein the surplus heat compression is employed for the generation of a blend of water vapor and air, or humidified air, which serves as the working fluid propelling air turbines. The results demonstrate a notable increase in round-trip efficiency. Nevertheless, it appears that a considerable quantity of residual heat is still available for utilization. The objective of this study is to enhance the efficacy of LAES through the implementation of a humidified discharge cycle in conjunction with combined heat and power generation in a central heating plant.

II. Content and Procedures

A. General Method

The following objectives and tasks were pursued: (i) brief introduction a baseline case, or a reference stand-alone LAES system with a humidified discharge cycle, which will be referred to as the power generation only setup, or Scenario A; (ii) creation a humidified discharge cycle configuration for combined heat and power generation located in a central heating plant (referred to hereinafter as Scenario B); (iii) Evaluation of a humidified discharge cycle configuration for combined heat and power generation in a newly built 4th generation central heating plant, which we shall refer to as Scenario C; (iv) A comparative analysis of the RTE for the above mentioned options A, B and C is presented in the following.

The methodology deployed in simulating operational scenarios and ascertaining the pivotal performance characteristics of the proposed systems is based on the utilization of specialized commercial software [2].

B. Baseline Case of a Standalone LAES System with a humidified discharge cycle: scenario A

The initial configuration of a standalone LAES system is based on a design that is physically and parametrically identical to the one proposed by Guizzi et al. [3] and subsequently examined in depth by Sciacovelli et al. [4]. In general, a LAES plant operates in three phases. During periods of excess power supply, which may originate from intermittent renewable sources, air is liquefied using electricity through the processes of refrigeration and compression (charge stage). Subsequently, a low-pressure insulated tank is employed for the storage of the liquefied air (storage stage). During periods of elevated power demand, the liquid air is then extracted from the tank, conveyed by means of pumping, and subjected to heating through the utilization of compression heat that has been previously stored. Subsequently, the compressed air is expanded in a turbine that

979-8-3503-9167-1/24/$31.00 ©2024 IEEE

is connected to a generator, thereby supplying the grid with power (discharge stage).

In order to prevent pipeline icing and ensure the safe operation of pipelines, it is necessary to remove high freezing point compounds (H_2O and CO_2) from the system prior to cooling ambient air during the air liquefaction process. This is a fundamental requirement of every LAES system. Therefore, the complete cycle of charging and discharging is conducted with completely dry air. This particular situation presents an optimal opportunity to significantly humidify the pumped air entering the expansion train, where the temperatures are sufficiently high to prevent any freezing.

The humidification concept presented in reference [1] demonstrates that as water vapor is absorbed into the air during the humidity increase, the air flow rate rises. This enables a greater proportion of the output from the expansion train to be utilized in the generator, thereby increasing the electricity yield.

As illustrated in Fig. 1, the integration of an air saturator into the LAES discharge cycle represents a viable approach to ensuring effective humidification processes. Table 1 provides the key data needed to evaluate the differences between dry air and humidified air configurations.

Table 1 provides the key data needed to evaluate the differences between dry air and humidified air configurations. From this point, it is possible to observe the advantages of the air entering the air turbines from the saturator being saturated with water vapor.

The additional thermal oil's waste heat energy is employed to achieve this air humidification. Consequently, instead of entering the atmospheric cooler for heat rejection at the considerably higher temperature of 474.50 K as in dry air case, the 9H thermal oil stream enters at 340.3 K.

This results in a reduction in the amount of heat dissipated into the atmosphere. If a 9-hour charge/3-hour discharge cycle is used, the heat loss will be reduced from 288.42 MWh to 72.3 MWh.

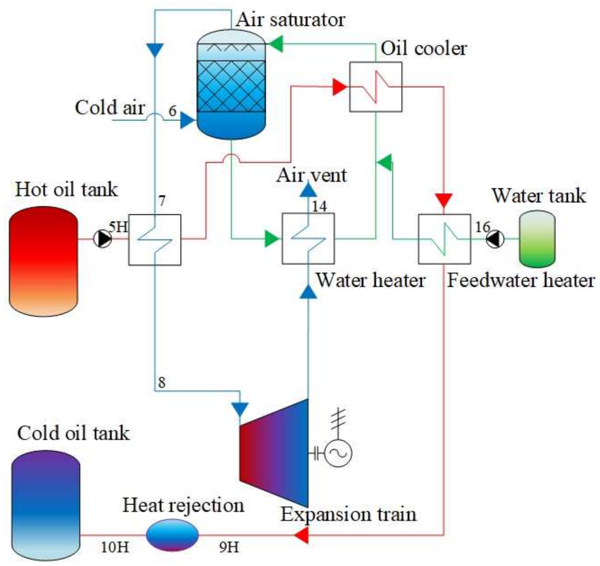

Fig. 1. The principal schematic of the humidified discharge cycle, scenario A, adopted from [1]

TABLE I. FLOW PARAMETERS MOST RELEVANT TO HUMIDIFICATION EFFECT (ADOPTED FROM [1])

№ Stream	Flow		Temperature	
	(kg/s)		(K)	
	dry air	humidified air	dry air	humidified air
6	211.80	211.80	268.50	268.5
7	211.80	236.6	437.70	268.5
14	211.80	236.6	281.10	319.6
16	n.a.	24.83	n.a.	293.8
5H	287.10	287.10	646.00	646.1
9H	287.10	287.10	474.50	340.3
10H	287.10	287.10	288.30	288.30
Wasted heat	dry air discharge		humidified air discharge	
kWh	96 140		24 100	

In spite of this, there is still a considerable amount of residual heat available for use. In addition, by optimizing the discharge process to maximize power generation, the temperature of the discharged air stream 14 is increased, andits residual heat is also released to the atmosphere. Both quantities are in the MW range and are therefore suitable for central heating purposes.

C. Humidified discharge cycle with combined heat and power generation in an existing central heating plant: scenario B

Central heating is widespread in the Nordic and Central/Eastern European countries. The shares of central heating in the consumption of energy for heating purposes (2015) for the European countries with suitable climate conditions and proper urban infrastructure vary from ten up to forty two percent (Source of Data: JRC 2019: Decarbonizing the EU heating sector). The largest central heating plants are usually located near large cities. In the Bulgarian capital, Sofia, 71% of the total heating energy demand is provided by four large heating plants operated by the local central heating company. The total length of the supply network is almost 2000 km. Sofia EAST CHP plant is used as reference case in this study. The actual heating capacity of Sofia East is 1253 MWth [4]. Main fuel source is natural gas. The plant operates year-round, providing sanitary hot water only during summer.

Sofia EAST cogeneration plant is based on 3rd generation central heating technology. Generally, this technology has been developed since the 1970s. It is based on hot water at temperatures <80°C by design and the network consists of insulated pipes buried directly in the ground. This is the most common type of central heating system in use today.

In central/district heating systems the heat transfer fluid is pressurized hot water, heated to the forward temperature at the heat supply units. It is then cooled to the return temperature at the customer substations. The forward temperature is determined by the heat provider, while the return temperature is the aggregated result of all cooling processes at the customer substations e.g. the actual heat consumption, and the losses of the system. It should be noted that the network temperatures are not standardized and will depend on local meteorological conditions. Normally the heat provider uses fixed schedules only for the forward temperature while the return one is beyond their control. The climate of Bulgaria is mild, with temperatures rarely falling below zero degrees Celsius for extended periods during the winter seasons [6]. As a consequence, both the forward and return water temperatures are relatively low. In consideration of the aforementioned heating scenario, the return temperature has been set at a constant value of 328.15 K. As shown above in Table 1 the temperature of the thermal oil at point 9H resp. after the power generation system is 340.3 K. It is higher than the return mains water temperature. This allows the thermal oil to be used to preheat the mains water in a suitable heat exchanger.

Sofia's central heating network is relatively old and, as mentioned above, and it is highly branched and long. Consequently, a considerable amount of permanent leakage occurs. This results in the necessity for the addition of a significant volume of makeup water to the network. The temperature of the added water from underground source is chosen 283.15 K from practical considerations and as well as its flow is fixed at 50 kg/s in compliance with the averaged data received from the power plant. The temperature of the humidified air leaving the power generation system at point 14 is 319.6 K. It is higher than the make-up water temperature. This allows the warm humidified air to be used to preheat the make-up water in a suitable heat exchanger. As a result of the preheating, the make-up water will increase its temperature while the humidified air will cool. In this cooling, some of the water vapor in it will liquefy. Directing the flow of humid air after the make-up water preheater to a separator will allow the resulting condensate to be separated and used as feed water to the LAES plant to humidify the cold air entering the saturation. The scheme for heating the make-up water and the return mains water is shown in Fig. 2.

As a result of preheating, the temperature of the make-up water rises from 283.15 K to 316.15 K. The return water temperature rises from 328.15K to 337.15K. In both cases described above, the preheating described in this way displaces preheating in the existing natural gas-fired facilities

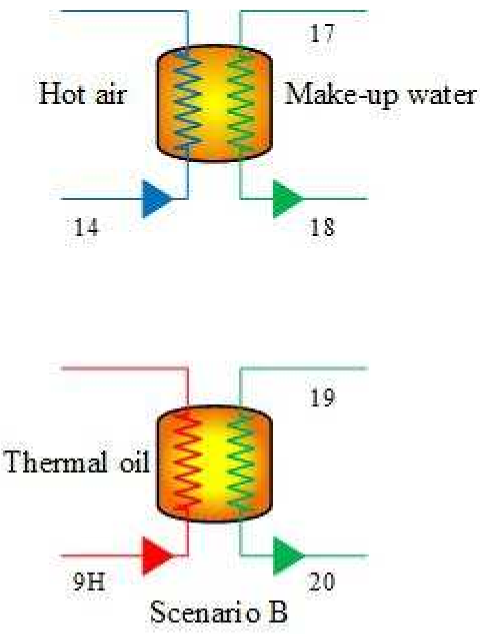

Fig. 2. Network water and make-up water heating scheme

at the plant. As a result, emissions of carbon dioxide and other environmental pollutants will be reduced.

D. Humidified discharge cycle with combined heat and power generation in a newly built central heating system: scenario C

This scenario includes the evaluation of the 4th generation central heating system (also known as 4GDH) as a suitable option for any new central heating system. A trend towards lower forward temperatures and higher energy efficiency is characterizing the development of central heating systems. The concept of the 4th generation central heating technology has been launched by Lund et al in [7]. Its essence is that 4GDH systems serve to provide the requisite heat supply of low-energy buildings with minimal grid losses, whereby the utilization of low-temperature heat sources is integrated with the operation of intelligent energy systems.

Typically, 3GDH has forward temperatures of around 353.15 K, whereas a 4GDH forward temperature in the range of 328.15 K to 338.15 K represents a relatively conservative level at which retrofitting is minimized while still allowing benefits to be reaped. In their subsequent study, Lund et al. defined the 4GDH temperature levels as 328.15 K for the forward temperature and 298.15 K for the return temperature [7]. These levels have been demonstrated to provide comfortable temperatures while ensuring Legionella safety with the appropriate installations in individual buildings. These recommendations are duly considered in the present study. The return water temperature is fixed at 298.15 K in the following analyses.

It is reasonable to assume that a highly efficient network serving 4GDH will exhibit negligible leakage. The heating of make-up water is not an actual problem in this case. As a result, the return water heating process makes use of both hot air and thermal oil streams. The cascade heating of the return water is performed, sequentially first in air water heater and then in thermal oil water heater. The scheme for heating the return mains water is shown in Fig. 3.

The low temperature of the return water, respectively the greater difference in temperatures of the heated and heating fluids, makes it possible to heat a significant amount of return water. Table 2 shows that scenario C produces twice as much heat as the previous case.

E. A comparative analysis of the RTE for the above mentioned options A, B and C is presented in the following

Summary of the simulation analyses and the obtained results during the assessment of Scenario B and Scenario C along with the data for Scenario A is presented at Table 2. The number of charging hours is fixed at 9 while the number of discharge hours reflect the duration of an evening peak load that takes place at every electrical grid. So, the time span of 3 hours was chosen as a peak duration.

The combined heat and power (CHP) efficiency RTE can be expressed with the following, considering the net power and heat production and the consumption of the LAES system during periods of low grid load (off-peak hours):

$$\eta_{CHP}=(P_{EG}+H_{HP})/P_{EC} \tag{1}$$

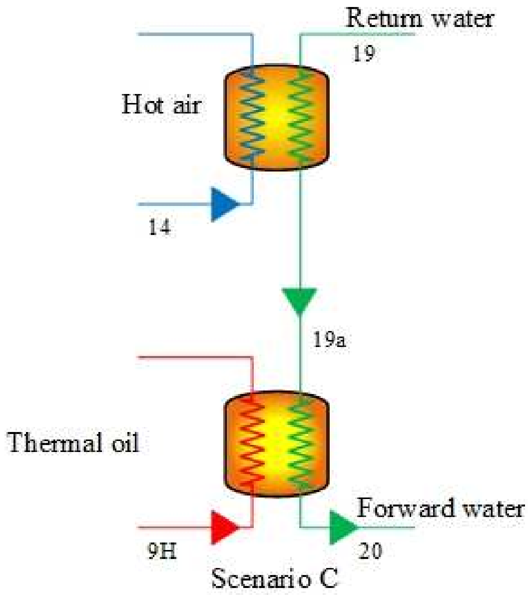

Fig. 3. Network water heating scheme

Where:

P_{EG} is the air turbines net energy generation, kWh;

H_{HP} is the discharge cycle heating production, kWh;

P_{EC} is the energy consumed for air liquefaction, kWh

The below table does not indicate the effect of cooling the outgoing moist air with low temperature mains water. In scenario A the total amount of condensate produced is 23.82 kg/s. In scenarios B and C, the condensate produced increases to 12.43 kg/s and 15.32 kg/s. In all three scenarios, the amount of demineralized water required to humidify the air is 24.82 kg/s.

III. Conclusions

The proposed combined heat and power generation concept for the discharge cycle of a LAES system has the potential to significantly enhance the system's efficiency. When assessed at a lower return water temperature which falls within the range typical of fourth-generation central heating systems, the roundtrip efficiency increased from 59% to nearly 71%. With the fifth generation of central heating, which is characterized by even lower return and forward water temperatures, further roundtrip efficiencies increase in excess of 80% can be expected.

A significant positive effect is the production of a significant amount of condensate up to 62% of the required amount of demineralized water needed to humidify the air. This will reduce the need for demineralized water and reduce the necessity for its production in the central heating plant.

TABLE II. A summary of the principal findings

Scenario A	Scenario B	Scenario C
Net power consumed for air liquefaction, KW		
71 019	71 019	**71 019**
Number of charging hours		
9	9	**9**
Net energy consumed for air liquefaction, kWh		
639 174	639 174	**639 174**
Net power generated by the air turbines, KW		
128 416	128 416	**128 416**
Number of discharge hours		
3	3	**3**
Air turbines net energy generation, kWh		
377 054	377 054	**377 054**
Net heating of air/water heater, kW		
n.a.	6 889	**14 998**
Net heating of oil/water heater, kW		
n.a.	4 417	10 013
Discharge cycle heating production, kWh		
n.a.	33 918	**74 988**
Round trip efficiency, %		
58.99	64.3	**70.7**

Acknowledgment

The authors would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support.

References

[1] A. Borissova, K. Hristov, and D. Popov, “An initial evaluation of humidified discharge cycle for liquid air energy storage” IOP Conference Series: Earth and Environmental Science, 2024, 1380(1), 012004, DOI 10.1088/1755-1315/1380/1/012004

[2] THERMOFLEX®. Thermoflow’s Suite. 2021. Available online: www.thermoflow.com/products_generalpurpose.html (accessed on 1 March 2024).

[3] G.L. Guizzi, M. Manno, L.M. Tolomei, and R.M. Vitali, “Thermodynamic analysis of a liquid air energy storage system.” Energy 93 (2), 1639-1647. https://doi.org/10.1016/j.energy.2015.10.030

[4] A. Sciacovelli, A. Vecchi, and Y. Ding, “Liquid air energy storage (LAES) with packed bed cold thermal storage – From component to system level performance through dynamic modelling”. Appl. Energy 190, 84-98. https://doi.org/10.1016/j.apenergy.2016.12.118

[5] Black & Veatch report: Upgrade, remediation, and capitalization feasibility study task 2 report, prepared for Sofia Municipality,24 SEPTEMBER 2021;

[6] K. Hristov, “Energy efficiency on combined heat and power production and heat supply at district heating system (in Bulgarian)”, Proceedings from the Energy Forum conference 2022, Varna, Bulgaria

https://inis.iaea.org/collection/NCLCollectionStore/_Public/53/125/53125044.pdf

[7] H. Lund, P.A. Østergaard, M. Chang, S. Werner, S. Svendsen, P. Sorknæs, et al. “The status of 4th generation district heating: research and results.” Energy, 164 (2018), pp. 147-159, https://doi.org/10.1016/j.energy.2018.08.206