

Load Shifting of Nuclear Power Plants Using Cryogenic Energy Storage Technology

Hari Kesavan H^{a*}, A. Kanni Raj^b, T. Elango^c

P.G Student, Department of Cryogenic Engineering, PSN College of Engineering and Technology, Tirunelveli,
Tamil Nadu, India

Professor, Department of Aeronautical Engineering, PSN College of Engineering and Technology, Tirunelveli,
Tamil Nadu, India

Assistant Professor, Department of Mechanical Engineering, Udaya School of Engineering, Kanyakumari,
Tamil Nadu, India

ABSTRACT: To balance the demand and supply at off-peak hours, nuclear power plants often have to be down regulated particularly when the installations exceed the base load requirements. Part-load operations not only increase the electricity cost but also impose a detrimental effect on the safety and life-time of the nuclear power plants. We propose a novel solution by integrating nuclear power generation with cryogenic energy storage (CES) technology to achieve an effective time shift of the electrical power output. CES stores excess electricity in the form of cryogen (liquid air/nitrogen) through an air liquefaction process at off-peak hours and recover the stored power by expanding the cryogen at peak hours. The combination of nuclear power generation and the CES technologies provides an efficient way to use thermal energy of nuclear power plants in the power extraction process, delivering around three times the rated electrical power of the nuclear power plant at peak hours, thus effectively shaving the peak. Simulations are carried out on the proposed process, which show that the round trip efficiency of the CES is higher than 70% due to the elevated topping temperature in the superheating process and thermal efficiency is also substantially increased.

KEYWORDS: Cryogenic energy storage, Nuclear power plant, System integration, System optimization

1. INTRODUCTION

Recent years have seen a renewed interest in increasing nuclear power generation in both developed and developing countries due to energy security and environmental considerations. The latter is also very much associated with reducing the carbon footprint because of the highest percentage of carbon emission from the power generation sector and very limited contribution from renewable energy to total power supply [1–4]. Nuclear power plants (NPPs) feature high capital costs and low operating costs. The costs of energy from such a capital intensive technology can be low if the facilities are operated at full capacity, and therefore NPPs have been mainly used as a base-load source of electricity production. However with increasing installations, the capacity of nuclear power may exceed the base load of power grids. For example, in France the nuclear power contributes about 53% of the country's total installation capacity and generates about 79% of the overall electricity [5, 6]. In these circumstances the excessive electricity at off-peak times has to be either exported to other countries or stored for later use. If the above measures fail to balance the generation and demand the NPPs have to be down regulated regularly. When the NPPs operate at a part capacity, the cost of electricity production becomes very high. Furthermore frequent changes in the load affect strongly on the aging of the equipment and the performance of the fuel, and hence causing problems in both the economic and safety aspects [7]

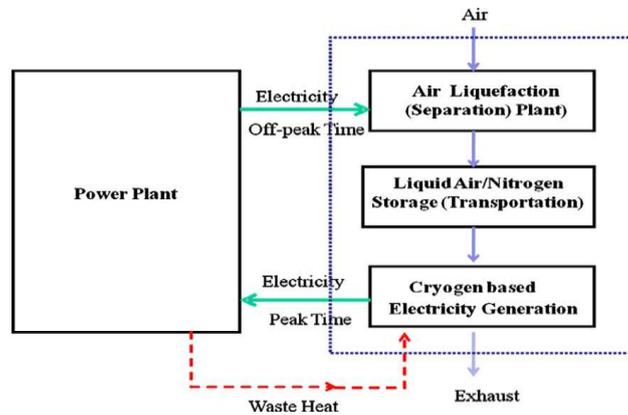


Fig. 1. Schematic diagram of a CES system.

A considerable effort has been made to deal with load-shift of NPPs and the conventional method is pumped hydro. More recent decades have seen the development of new approaches to the use of excess electricity for maintaining the NPPs at nearly the full load. These include steam accumulator storage [8], large scale hydrogen production and storage [9–12] and geothermal heat storage [13]. Here we propose the use of cryogenic energy storage (CES) for the load shift of NPPs. CES is a large scale energy storage technology which uses cryogen (liquid air/nitrogen) as a storage medium and also a working fluid for energy storage and release processes. A schematic diagram of the CES technology is shown in Fig. 1 [14, 15]. During off-peak hours, when electricity is cheapest and demand for electricity is lowest (typically during nights and weekends), liquid air/nitrogen is produced in an air liquefaction and separation plant and stored in cryogenic tanks at close to the atmospheric pressure. During peak hours, the cryogenic liquid is heated up by using the environmental heat and then super-heated using other heat sources (if available). Boiling of the cryogenic liquid will form a high pressure gas to drive an expander (e.g. turbine) to produce electricity.

II. THE PROPOSED SYSTEM

2.1. The pressurized water NPPs and load regulation

Pressurized water NPPs account for a large portion of the world’s nuclear power plants [35, 36]. Fig. 2 shows the schematic diagram of a typical pressurized water NPP. Nuclear fuel in the reactor vessel is engaged in a fission chain reaction, heating primary coolant (water) in the primary coolant loop. The heated primary coolant is pumped by Pump 1 into the high pressure side of Heat exchanger 1 to transfer heat to the secondary coolant (water) in the low pressure side of the heat exchanger, leading to vaporization of the secondary coolant to give high pressure steam. The high pressure steam then expands in a steam turbine, which drives Generator 1 to produce electrical power. After the expansion in the turbine, the working fluid becomes water–steam mixture, which, upon cooling down, condenses in the Cooling tower to give liquid phase water. The water is then pumped back into Heat exchanger 1 by Pump 2, completing the cycle.

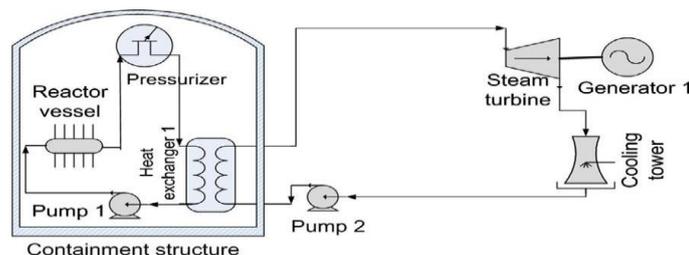


Fig. 2. Schematic diagram of a typical pressurized water NPP.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

Down-regulation of the load of pressurized water NPPs in the cases of low demands includes the control assemblies being inserted into the reactor vessel and associated changes of the cool-ants [37]. Apart from the safety issue and lifetime reduction, such operation modes also suffer two challenges in load following. First is the limited power changing gradient which normally takes a few hours to achieve about half load. Second is that the down-regulation of NPPs only balances the generation and demand at trough hours while other plants such as gas-fired power stations have to be employed to meet the peak demands.

2.2. The Proposed NPP–CES System

An integrated NPP and CES system is proposed in the present paper, which has the potential to resolve the issues associated with the load regulation of NPPs. Fig. 3 shows the principle of the integrated system, which consists of a NPP sub-system and the CES sub-system. The NPP sub-system in the integrated system is similar to the conventional pressurized water NPP as shown in Fig. 2. The only difference lies in that there are two three-way valves in the secondary loop, which enables the working fluid to feed into either the steam turbine to produce electricity or Heat exchanger 4 to super heat high pressure air in CES sub system (see Fig. 3). The CES sub system consists of an air liquefaction unit in the left part and a cryogenic energy extraction unit in the right bottom part of Fig. 3. The integrated system has three operational modes depending on the end-users' demands:

- (1) **Energy storage mode:** At trough hours when the demand is much lower than the rated power of the NPP, the NPP operates in a traditional way to drive the steam turbine to produce electricity and the excessive power is used to drive the air liquefaction unit to produce liquid air (energy is stored in liquid air). In this process, dry air stream (2) and return gas stream (10) are mixed and compressed to an elevated pressure (5) by a two-stage compressor (Compressor 1 and Compressor 2) with inter-cooling (3–4) in Heat exchanger (5). After rejecting heat via Heat exchanger 6 in the main cold box (Process 5–6), the high pressure air is cooled to the lowest temperature level, followed by a near-isentropic expansion process in the so-called Cryoturbine to give liquid air. A fraction of the product is vaporized in the cryogenic tank and introduced back to the main cold box through Heat exchanger 6 and the inter-cooler Heat exchanger 5 to supply part of the cold energy. The remaining cold requirement of the main cold box is met by the cold stored in Thermal fluid tanks (see more details in later discussion).
- (2) **Energy release mode:** At peak hours when the demand is higher than NPP's rated power, the cryogenic energy extraction unit is turned onto produce additional power. In this process, liquid air in Liquid air tank is pressurized first by the Cryogenic pump. The high pressure air transfers its cold energy to the cold storage media in Process 16–17 via Heat exchange 2 followed by a pre-heating process in Heat exchanger 3 by the exhaust gas stream (Process 26–27). In the meantime, the secondary coolant in NPP is introduced into Heat exchanger 4 by switching on the three-way valves. This leads to further increase in the temperature and pressure of the air, which, upon expansion in a four-stage air turbine with inter-heating in Heat exchanger 4, drives Generator 2 to produce electricity. The exhaust air is used first to preheat the high pressure air in Heat exchanger 3 and then to regenerate the desiccant in Dryer.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

aims to recover the cold energy released during liquid air preheating process. In this process air is under the supercritical state, and as a result the cold is produced in the form of sensible thermal energy. Fig. 4 shows the isobaric heat capacity of air as a function of temperature at different pressures. One can see that the isobaric heat capacity of air changes only slightly in the heating process, particularly at very high pressures. Similar to the use of liquids to store sensible heat, cold energy can also be stored in thermal fluids (see below) and such fluids can give good temperature gradient match during heat exchange and hence an efficient cold recovery. In this process the thermal fluids are used not only as a working fluid but also as a cold storage medium.

From the above discussion, selection of correct thermal fluids is important. Fig. 5 shows the isobaric heat capacities of some commonly used refrigerants. Clearly, no single fluid can fully cover the working temperature region of liquid air pre heating process. The combination of propane and methanol works as both the cold storage liquids and the working fluids for heat transfer, which cover the required temperature range and have a high heat capacity. For each of the two fluids, a two tank configuration is proposed for cold recovery and storage; see Fig. 3. The two thermal fluids are pumped from the hot tanks to the cold tanks during the cold storage process (the energy releases mode), and flow back during cold release process (the energy storage mode). The use of thermal fluids for both transferring and storing thermal energy can greatly simplify the design of the system in that no additional heat exchangers will be needed. Moreover, the operating strategy can be much straighter forward the amount of cold energy and the objective temperature can be easily adjusted by controlling the flow rate of the fluids. This is extremely difficult to achieve using the conventional way of storing cold in a packed pebble bed.

The cryogenic energy extraction unit is coupled with the NPP through the thermal energy utilization process via Heat exchanger 4. One can see that hardly any thermal energy is wasted in the cooling process and hence the power output is expected to increase significantly. By integrating with CES technology the reactor core and the primary loop of NPPs operate steadily at full load at all times while the net output power is adjusted only by the CES unit. As the energy extraction process in the CES sub-system is similar to power generation using a gas turbine, a much faster rate of power change could be achieved in comparison with the conventional down-regulation of NPPs.

III. DISCUSSION ON THE OPERATING CONDITIONS

In this section, discussion is made on possible ways to enhance the performance of the integrated NPP – CES system. First, the storage pressure effect is investigated. Thermodynamics tells that the higher the pressure, the easier the gas can be liquefied and hence a higher CES round trip efficiency could be achieved [21]. We therefore investigated the influence of the storage pressure on the NPP – CES integrated system. Fig. 6 shows the results. An increase in the storage pressure shows a linear increase in the round trip efficiency and the increase rate is about 0.8% per bar increased. This indicates that the storage pressure affects mainly the liquefaction process as both the net output power and the mass flow-rate of liquid air in the energy release mode changes only slightly with increasing storage pressure. Here the almost constant net output power is because the increased storage pressure reduces only the power consumption of the cryogenic pump.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

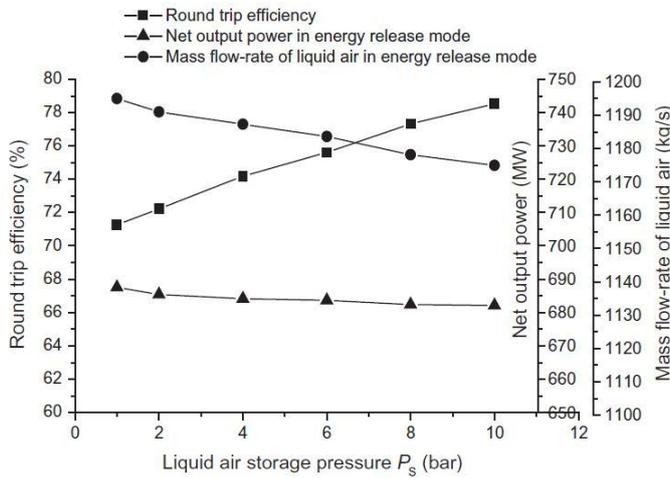


Fig. 6. The influence of liquid air storage pressure. the NPP.

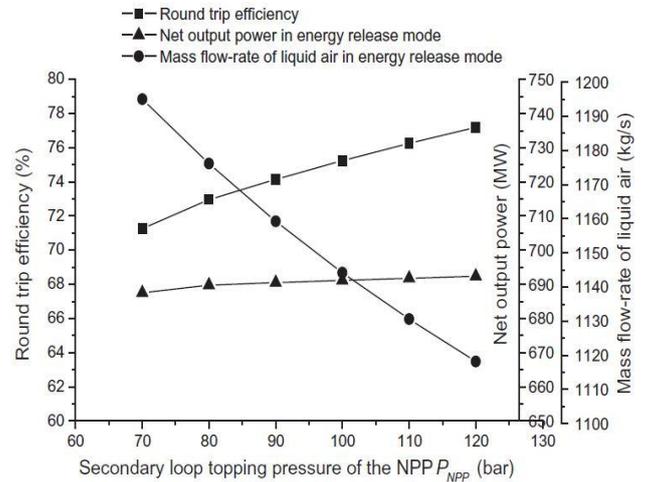


Fig. 7. The influence of secondary loop topping pressure of the NPP.

Second, the effect of the secondary loop topping pressure of the NPP in energy release mode is examined. In the energy release mode of the integrated system, the steam in the secondary loop of the NPP is used to superheat the high pressure air instead of driving the steam turbine. Fig. 7 shows the results. One can see an almost linear increase in the round trip efficiency with increasing secondary loop topping pressure. Different to the influence of the storage pressure, the mass flow-rate of liquid air in the energy release mode decreases with increasing secondary loop topping pressure. This indicates the secondary loop topping pressure affect mainly on the energy release mode. Although the mass flow-rate of liquid air decreases, the net output power is seen to be almost independent of the topping pressure.

It should be noted that the increase in either the energy storage pressure or the NPP secondary loop topping pressure could face technical and economic challenges. For example, currently cryogenic tanks are typically operated at a pressure below 10 bars at a 100 ton scale and generally at the atmospheric pressure for over 100 ton scales. As a consequence the selection of the working pressures should consider the balance between the system performance and the capital, operation and maintenance costs.

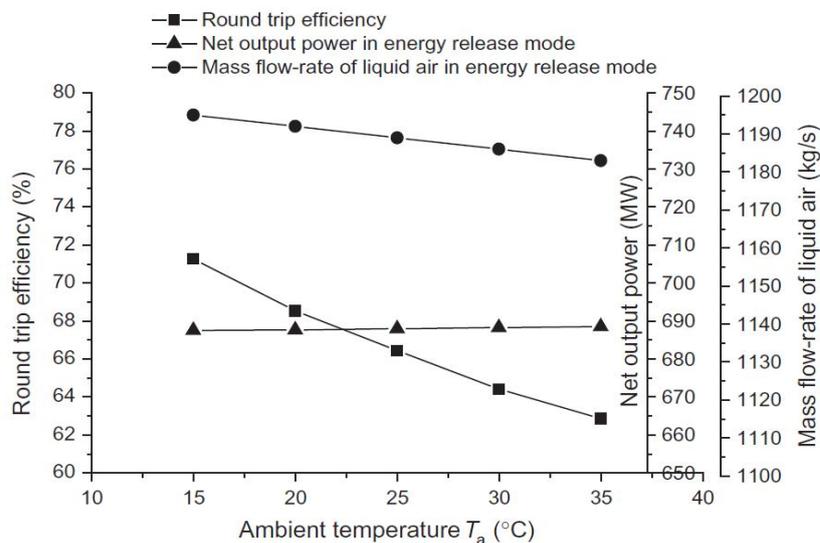


Fig. 8. The influence of the ambient temperature.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

Third, the ambient temperature is expected to have some effect and this is investigated and the results are shown in Fig. 8. The round trip efficiency is seen to decrease by about 2% for every 5 LC increase in the ambient temperature. Similar to the storage pressure, the ambient temperature has a much stronger effect on the air liquefaction process than that on the energy release process in terms of the net output power (The mass flow-rate of liquid air in energy release mode changes very slightly with the increase of the ambient temperature). This agrees well with the fact that the power consumption of LNG plants in arctic regions such as Norway is much lower than those in other regions [42, 43]. These results also indicate that locations with a low ambient temperature are preferred for the installation of NPP–CES integrated systems.

The above analyses also indicate that the net output power in the energy release mode changes very slightly around about 690 MW. As a result, the integrated system is capable of generating some 2.7 times the power at peak demands compared with a NPP alone system, regardless of the location of the installation and the operating pressures.

IV. CONCLUSION

A new system for meeting different loads in electrical grid has been proposed in this work. Such a system integrates the nuclear power plant and the cryogen based energy storage technology. Thermodynamic analyses are carried out on the system under fairly general baseline assumptions and the results show that the round trip efficiency of electrical energy storage is about 71% while the net output power in the energy release mode is about 2.7 times that in a nuclear power plant alone. The round trip efficiency is similar to the pumped hydro storage method while the proposed technology does not rely on any favorable geography (except for the NPP sites). This provides a potential method to change the net power output of NPPs instead of down-regulating the NPPs regularly. Sensitivity analyses are carried out on the operating condition and the results show that the storage pressure and ambient temperature mainly affect the air liquefaction process while the secondary loop topping pressure of the NPP affects more on the energy release process.

The modeling work has shown competitive performance of the integrated system which enables base-load nuclear power generation to play a flexible role in load shifting. The integration is likely to be practically feasible as modification to current NPP is only on the secondary loop (steam Rankine cycle) and such modification can be achieved with on-shelf technologies. The main obstacle, in our view, to bring such a technology to real-world applications is the lack of revenue mechanism under current market conditions. Further work is therefore needed to study the economic and policy aspects associated with the integrated system in addition to an experimental or demonstration study.

REFERENCES

- [1] Cai W, Wang C, Wang K, Zhang Y, Chen J. Scenario analysis on CO₂ emissions reduction potential in China's electricity sector. *Energy Policy* 2007; 35: 6445–56.
- [2] Krackeler T, Schipper L, Sezgen O. Carbon dioxide emissions in OECD service sectors: the critical role of electricity use. *Energy Policy* 1998; 26:1137–52.
- [3] Tzimas E, Georgakaki A, Peteves S. Reducing CO₂ emissions from the European power generation sector – scenarios to 2050. *Energy Procedia* 2009; 1: 4007–13.
- [4] Adamantiades A, Kessides I. Nuclear power for sustainable development: current status and future prospects. *Energy Policy* 2009; 37:5149–66.
- [5] Bruynooghe C, Eriksson A, Fulli G. Load-following operating mode at nuclear power plants (NPPs) and incidence on operation and maintenance (O&M) costs. Compatibility with wind power variability. European commission, Joint research centre, Institute of energy; 2010.
- [6] Coombs C. French nuclear power: a model for the world? *Hinckley J Politics* 2010:7–13.
- [7] Likhov A. Technical and economic aspect of load following with nuclear power plant. Nuclear energy agency, organisation for economic co-operation and development; 2011.
- [8] Gilli PV, Beckman G. Steam storage adds peaking capacity to nuclear plants. *Energy Int* 1973; 10:16–8.
- [9] Forsberg C. Futures for hydrogen produced using nuclear energy. Great Britain: Elsevier Ltd; 2004.
- [10] Forsberg CW. Economics of meeting peak electrical demand using nuclear hydrogen and oxygen; 2007.
- [11] Yildiz B, Kazimi MS. Efficiency of hydrogen production systems using alternative nuclear energy technologies. *Int J Hydrogen Energy* 2006; 31: 77–92.
- [12] Forsberg CW, Kazimi MS. Nuclear hydrogen using high-temperature electrolysis and light water reactors for peak electricity production. Massachusetts Institute of Technology; 2009.
- [13] Forsberg CW, Lee Y, Kulhanek M, Driscoll MJ. Gigawatt-year nuclear-geothermal energy storage for light-water and high-temperature reactors. In: International congress on the advances in nuclear power plants, Chicago, Illinois; 2012.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

- [14] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: a critical review. *Progr Nat Sci* 2009; 19:291–312.
- [15] Knight H. Liquid air stores power. *New Scientist* 2011; 209:21.
- [16] Smith EM. Storage of electrical energy using supercritical liquid air. *ARCHIVE ProcInstMechEng* 1847–1982 1977; 191:289–98.
- [17] Kenji K, Keiichi H, Takahisa A. Development of generator of liquid air storage energy system. *Technical Review*. Vol. 35. Mitsubishi Heavy Industries, Ltd.; 1998. p. 4.
- [18] Chino K, Araki H. Evaluation of energy storage method using liquid air. *Heat Transfer—Asian Res* 2000; 29:347–57.
- [19] Araki H, Nakabaru M, Chino K. Simulation of heat transfer in the cool storage unit of a liquid–air energy storage system. *Heat Transfer—Asian Res* 2002; 31: 284–96.
- [20] Wakana H, Chino K, Yokomizo O. Cold heat reused air liquefaction/ vaporization and storage gas turbine electric power system. Hitachi Ltd; 2005. p. 30 [US Patent ed.].
- [21] Vandor D. System and method for liquid air production, power storage and power release. US States Patent ed. Expansion Energy, LLC; 2011.
- [22] Chen H, Ding Y, Peters T, Berger F. Energy storage and generation. Highview enterprises limited; 2009. p. 70 [USPA Publication ed.].
- [23] Ding Y, Wen D, Dearman PT. Cryogenic engines. Highview Enterprises Limited; 2009. p. 9 [USPA Publication ed.].
- [24] Li Y, Jin Y, Chen H, Tan C, Ding Y. An integrated system for thermal power generation electrical energy storage and CO₂ capture. *Int J Energy Res* 2011; 35:1158–67.
- [25] Li Y, Wang X, Ding Y. A cryogen-based peak-shaving technology: systematic approach and techno-economic analysis. *Int J Energy Res* 2011.
- [26] Li Y, Wang X, Jin Y, Ding Y. An integrated solar-cryogen hybrid power system. *Renew Energy* 2012; 37:76–81.
- [27] Chen H, Ding Y, Li Y, Zhang X, Tan C. Air fuelled zero emission road transportation: a comparative study. *Appl Energy* 2011; 88:337–42.
- [28] Ordonez CA, Plummer MC. Cold thermal storage and cryogenic heat engines for energy storage applications. *Energy Sources* 1997; 19:389–96.
- [29] Ordonez CA. Liquid nitrogen fueled, closed Brayton cycle cryogenic heat engine. *Energy Convers Manage* 2000; 41:331–41.
- [30] Hu Y, Li X, Li H, Yan J. Peak and off-peak operations of the air separation unit in oxy-coal combustion power generation systems. *Appl Energy* 2013.
- [31] Brett G. Cryogenic energy storage: introduction. vol. 2011. Highview Power Storage; 2011.
- [32] Li Y, Chen H, Ding Y. Fundamentals and applications of cryogen as a thermal energy carrier: a critical assessment. *Int J Thermal Sci* 2010; 49:941–9.
- [33] Li Y, Chen H, Zhang X, Tan C, Ding Y. Renewable energy carriers: hydrogen or liquid air/nitrogen? *Appl Thermal Eng* 2010; 30:1985–90.
- [34] Rosen MA. Energy- and exergy-based comparison of coal-fired and nuclear steam power plants. *ExergyInt J* 2001; 1:180–92.
- [35] Michaelides EE. Nuclear power plants: alternative energy sources. Berlin, Heidelberg: Springer; 2012. p. 131–72.
- [36] Kothare MV, Mettler B, Morari M, Bendotti P, Falinower CM. Level control in the steam generator of a nuclear power plant. *IEEE Trans Control SystTechnol* 2000; 8:55–69.
- [37] Ludwig H, Salnikova T, Stock A, Erlangen UW. Load cycling capabilities of German nuclear power plants. *Int J Nucl Power* 2010; 55:2–8.
- [38] Liquid expanders in LNG liquefaction plants. *World Pumps* 2002; 2002. p. 16.
- [39] Hylton EH, Kimmel HE. Exducer turbines, the optimized solution for LNG expanders. Ebara International Corporation; 2002.
- [40] Haesloop B, Kimmel HE. Improved cryogenic gas processing efficiency due to advancements in liquid turbine expanders. In: AICHE Spring national meeting, Sparks, Nevada, USA; 1998.
- [41] Cao W-S, Lu X-S, Lin W-S, Gu A-Z. Parameter comparison of two small-scale natural gas liquefaction processes in skid-mounted packages. *Appl Thermal Eng* 2006; 26:898–904.
- [42] Rian AB, Ertesvåg IS. Exergy evaluation of the arctic snøhvit liquefied natural gas processing plant in northern Norway—significance of ambient temperature. *Energy Fuels* 2012; 26:1259–67.
- [43] Mosbergvik OA. Statoil to begin Snøhvit LNG operations by yearend 2007. *Oil Gas J* 2007; 105:48–56.