ICMIEE20-KN01

Lunar Surface Sustainability: A Permanent Human Settlement on the Moon

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ABSTRACT

With the Artemis program, The United States plans to return to the Moon and create a permanent human presence in the lunar south pole before the next decade. Lunar poles and cislunar space offer a great option to expand human settlement beyond the planet earth. Scientific and economic opportunities of such human settlement are enormous. However, a paradigm of new technologies: *In-Situ Resource Utilization, Sustainable Power, Dust Mitigations, Precision Landing, Surface Excavation and Construction, Cryogenic Fluid Management, Extreme Access/Extreme Environment, and Communication and Navigation Systems* need to be deployed to support a long-term lunar habitat. The development and testing of large-scale industrial systems that can autonomously operate in extreme thermal and dust environment to extract and utilize lunar resources for human habitation are critically needed. This presentation provides an overview of the key technical challenges of human settlement on the Moon.

International partnerships will be critical in ensuring a sustainable and robust human settlement on the Moon. The United States has established the Artemis Accords to develop a global coalition for peaceful exploration of the Moon. Lunar exploration can create global harmony and prosperous relationships among nations. Artemis Accords focuses on, among others, Peaceful Exploration, Transparency, Interoperability, Space Resources, and Release of Scientific Data. To date, Australia, Canada, Italy, Japan, Luxembourg, United Arab Emirates, the United Kingdom, and the United States of America have joined the effort. Bangladesh should aspire and actively engage in getting an opportunity to join this global coalition.

The name Artemis is derived from the Greek goddess of the Moon and twin sister to Apollo. The world will need an Artemis generation of young engineers, scientists, and explorers from every corner of the globe to meet humanity's ambition to become a multi-planet species. A global engagement and investment for talent development and innovation will be essential for sustainable human presence beyond the lower earth orbit.

Keywords: Lunar Exploration, Artemis, Human Settlement, and In-Situ Resource Utilizations.

International Conference on Mechanical, Industrial and Energy Engineering 2020
19-21 December, 2020, Khulna, BANGLADESH

ICMIEE20-KN02

Research and Development of Next Generation Refrigerants and Refrigeration Systems

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ABSTRACT

After the innovative development of machine refrigeration in the nineteenth century, refrigerants used as working fluid in the refrigeration machine have changed in response to safety and environmental issues. And the refrigeration systems have also been designed to adapt the refrigerants. Currently used refrigerants called the third generation are facing regulations of production amount and usage methods because of global warming. In the Kigali amendment of the Montreal Protocol, the reduction of Hydrofluorocarbons which are the most widely used refrigerants is severely scheduled for developed countries, developing countries of groups 1 and 2, respectively. To satisfy the reduction schedule of the Kigali amendment is not so easy because there is very limited number of refrigerants that have low global warming potential (GWP) and safe properties such as no flammability and lower toxicity. And, each heat pump and refrigeration system demands suitable thermophysical properties for their operating conditions. Because the numerous number of operating conditions which are temperature, capacity and others exist, newly proposed pure refrigerants cannot cover all the systems. To fit the suitable thermophysical properties with acceptable GWP and safety properties, a lot of refrigerant mixtures with two to six components have been proposed and further searches are continuously carried out. Accurate estimation of thermophysical properties of new pure and mixture refrigerants is needed for the design and simulation of refrigeration systems. Therefore, measurements of the thermophysical properties are intensively being conducted. Drop-in tests of the new refrigerants are also being conducted. In this paper, the recent situation of next generation refrigerants and refrigeration systems are briefly reported.

Keywords: Refrigerant, Mixture refrigerant, Thermophysical property, HFO, GWP.

1. Introduction

In recent years, disasters due to abnormal weather occur all over the world. In Japan, especially, we suffer many disasters of heavy rain, floods, and typhoons almost every year. At COP25 held in Madrid in December 2019, an environmental think tank from Germany reported that Japan was the worst-hit by extreme weather in 2018. In 2019, there were a massive flood in August, and two strong typhoons in September and October. And, in 2020, we damaged by two massive floods caused by heavy rain in different areas in July. Not only typhoon and rain but also atmospheric temperatures are damaging us. Summer in recent years, the atmospheric temperature often reaches near or over 40 °C and we are threatened by heatstroke. Many people die every year. In 2018, more than 1500 people died from heatstroke in Japan. Atmospheric temperature is rising and such a high temperature is not normal.

It is considered that this abnormal weather is caused by Global Warming due to the increasing concentration of carbon dioxide in the atmosphere. Effects of refrigerants used in air-conditioners, refrigerators, and others on the Global Warming were first pointed out in the Kyoto protocol adopted in COP3 in 1997. Research on low Global Warming Potential (GWP) refrigerants was started against this background. Although researches and developments on low GWP refrigerants, fourth generation [1], were started, the effect of refrigerants on Global Warming was considered very small compared to carbon dioxide emitted by the combustion in power plants, manufacturing processes, cars, etc. After the decades of this, the situation was changed and the effect of the refrigerant became larger than before. And, in the Kigali Amendment of the Montreal Protocol, the regulation which is a phase down of refrigerants with high GWP has been adopted. McLinden [2] reported according to the analysis of Velders that the temperature increase will be around 0.3~0.5 K if the refrigerants are continuously used as the present conditions. Most of the refrigerants used in present air conditioners and refrigeration systems have high GWP from several thousand to over ten thousand. Even R32 which has relatively low GWP and is increasing its usage in air conditioners has a GWP value of 675.

In my previous paper [3], four ways of next generation refrigerants and heat pump/refrigeration systems were reported such as (1) natural refrigerants, (2) low GWP synthetic refrigerants, (3) refrigerant management, (4) refrigerant mixtures. Although the research and development on the next generation refrigerant and refrigeration systems are conducting intensively and some of them were solved, there are still issues remains. In this paper, a review and present situation of the research and development is reported.

2. History of refrigerant development

Here, a history of refrigerant development is briefly explained. A more detailed history is available in a report by McLinden and Huber [4]. An overview of refrigerant history is shown in Fig.1. At the first era when refrigerant machines were produced, many kinds of fluids were tried and used as refrigerants which are called the first generation. Some of them are toxic, some are flammable, and low efficiency. They were not suitable for the refrigerant. Only the ammonia NH_3 is continuously used so far though it is toxic and flammable. Carbon dioxide

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CO_2 started again to use as a refrigerant in Eco-cute which is a heat pump water heater. And, one of the hydrocarbons (HCs), isobutane, was used in domestic refrigerators.

The revolution of refrigeration was caused by the invention of Chlorofluorocarbons (CFCs) in 1920s and Hydrochlorofluorocarbons (HCFCs) in 1930s. Dichloro-difluoromethane (R12) which is non-toxic and non-flammable was commercially produced in 1931 and was used as a refrigerant in refrigerators. R22 which is one of the HCFCs was also commercialized in 1930s and it was used in air-conditioners which was widespread in 1950s. The evolution of refrigeration, air-conditioning and cold chain industries were brought about by non-toxic and non-flammable CFCs and HCFCs.

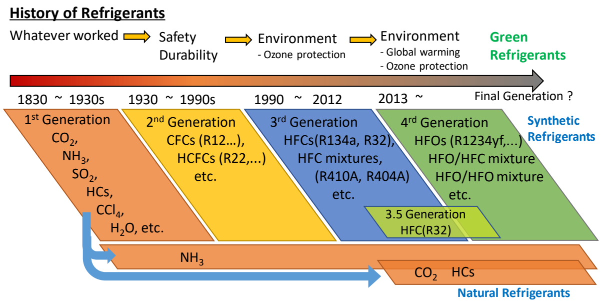

Fig.1 Overview of refrigerants history

However, as well known, the severe depletion of the ozone layer demanded strongly to phase out the CFCs and HCFCs. Currently, CFCs and HCFCs have almost phased out in most of the developed countries and are phasing down in developing countries. As alternative refrigerants of CFCs and HCFCs, Hydrofluorocarbons (HFCs) which do not deplete the ozone layer are developed and the usage of HFCs has been spread in 1990s. Representative HFCs are R23, R32, R125, R134a, R143a, R152a, etc. Because properties of these pure HFCs are limited in suitable pressure and non-flammability, mixtures of HFCs have also been developed. The representative mixtures are R404A (R125/R143a/R134a), R407C (R32/R125/R134a), R410A (R32/R125), etc. They are called the third generation refrigerants.

Although the usage of HFCs and their mixtures has been spread successfully and the crisis situation of ozone layer depletion seems to have been escaped, we are still facing the problem of Global Warming. After the Kyoto protocol, regulations on high GWP refrigerants were established and research and development are accelerated. For example, R134a used in most domestic refrigerators was replaced by isobutane. Eco-cute which is a heat pump water heater used CO_2 as a refrigerant was developed and spread the usage. Despite the efforts of researchers and engineers, the reduction of HFCs emission was not sufficient and the prevention of global warming was not enough. Therefore, further reduction and regulation were required. In accordance with the Kigali Amendment in 2016, the production and consumption of HFCs have to be reduced 85 % by 2036 in developed countries, 85 % by 2047 in developing countries of group 2, and 80 % by 2045 in developing countries of group 1, respectively. Reduction targets in the way are also scheduled. This reduction schedule is not easy to achieve because we have a limited number of new low GWP refrigerants and some of them have flammability and toxicity problems to be solved. Development time to achieve the reduction schedule is also limited. Currently, screening of promising pure refrigerants has almost been completed and many kinds of refrigerant mixtures with a variety of concentrations are being proposed [5].

3. Measures to prevent global warming caused by refrigerants

There are various factors affecting global warming. The emission of refrigerant to the atmosphere is one of the direct factors. Therefore, the replacement of high GWP refrigerants with low GWP refrigerants is the most important and urgent issue. Because the energy consumption of refrigeration systems also affects CO_2 emission and global warming as an indirect factor, the efficiency of the refrigerant is also important.

Hydrofluoroolefins (HFOs) are getting attention as alternative refrigerants because HFOs have zero-ODP and very low GWP. And, hydrochlorofluoroorefins (HCFOs) are also recently getting attention though they have non-zero-ODP in which the ODP values are very small. The reason for the attention to HCFOs is due to the limitation of proper thermophysical properties of proposed HFOs. Other low GWP refrigerants are hydrocarbons (HCs), carbon dioxide (CO_2, R744), and ammonia (NH_3, R717) which are called natural refrigerants. As well known, HCs have strong flammability and NH_3 is toxic and low flammable. CO_2 has low critical temperature, high pressure, and (in general) low cycle efficiency.

Promising refrigerant candidates to replace the current high GWP refrigerants are shown in Table 1 by ASHRAE designation number. Most of the current refrigerants are non-toxic, non-flammable and pure or behave as pure refrigerants which are azeotropic or quasi-azeotropic. In general, pure refrigerants have better performance and easier to handle than mixed refrigerants. Of course, non-toxic and non-flammable refrigerants are desirable. As shown in Table 1, non-flammable pure HFO and HCFO which are red-colored numbers are only for R123 which is mainly used in turbo chiller. R1234yf and R1234ze(E) are mildly flammable and both of them are alternate of R134a. Azeotropic mixtures which are R500 cerise are very limited, only R513A, R516, and R514A. The majority of the candidates are zeotropic mixtures which are R400 cerise. And, many other mixtures that are not listed are proposed. Although it seems that many candidates exist sufficiently for each current refrigerant, the actual situation is different. The mixtures listed in the non-flammable column have somewhat high GWP which cannot satisfy the Kigali amendment. Mixtures listed in mildly-flammable column can only be used for restricted systems because of safety problems mentioned in regulations, building codes, etc. Additionally, as explained above, zeotropic mixture refrigerants may have lower performance. And there is a lack of accurate thermophysical property data.

We need to find out the best alternative refrigerant for each current refrigerant. And reliable thermophysical property data are indispensable to design heat exchangers, compressors, systems, and other equipment. The thermophysical properties are also needed for refrigerant transportation, safe handling, and environmental treatment.

Table 1 Representative current refrigerants and promising alternative refrigerants.

Current (GWP)	Non-Flammable	Mildly Flammable	Flammable
R134a (1430)	R450A, R513A (HFC/HFO) R744 (CO2)	R516 (HC/HFO) R1234yf (HFO) R1234ze(E) (HFO)	R290 (propane) R600a (iso-butane)
R404A (3920) R507 (3990)	R448A, R449A/B (HFC/HFO) R452A, R452C (HFC/HFO) R744 (CO2)	R465A (HFC/HFO/HC) R457A, R454C (HFC/HFO) R455A (HFC/HFO/CO2) R717 (ammonia)	N/A
R410A (2090)	R466A (HFC/CF3I)	R32 (HFC) R459A, R447A, R452B, R454C (HFC/HFO)	R443A (R1270/290/600a) (CO2/HC) (R1270(propylene))
R123 (77)	R1233zd(E) (HCFO) R514A (R1336mzz(Z)/t-DCE) R1336mzz(Z) (HFO) R1224yd(Z) (HCFO)	N/A	N/A
R22 (1810)	R448A (HFC/HFO) R449A, R449B (HFC/HFO)	R457A, R454C (HFC/HFO)	R290 (propane) R443A (R1270/290/600a)
R23 (14800)	R469A(HFC/CO2)	N/A	N/A

The usage of natural refrigerants is also expanding in some fields. As mentioned, isobutane is used in most domestic refrigerators. Because the charge amount limit of propane was increased from 150 g to 500 g, the usage of propane will expand. The usage of CO_2 is spreading not only to heat pump water heaters but also to showcases in supermarkets and convenience stores. NH_3 refrigeration system is increasing in cold storage warehouses.

Because current refrigerants are needed to use transiently until suitable alternative refrigerants have been established, refrigerant management is necessary. Reduce, recover, reuse, and destruction of refrigerants are also needed. The refrigerant management is conducted in accordance with rules determined in each country. We need to strengthen and expand the refrigerant management. The refrigerant managements prevent leakage of refrigerants to the atmosphere and can mitigate Global Warming caused by the current refrigerants.

4. Importance of accurate thermophysical properties of new refrigerants

To use the new refrigerants in various refrigeration systems, thermodynamic and transport properties are essential for designing heat exchangers, compressors, and entire systems. Based on accurate measurements of thermodynamic properties which are pressure-volume-temperature relation, vapor pressure in saturation condition, critical parameters, specific heat of ideal gas condition and sound speed, equation of state (EOS) of is built and other state quantities such as enthalpy and entropy are calculated by using the EOS. When the EOS installed in a software, the thermodynamic properties can be calculated arbitrarily. In REFPROP [6] which is a wildly used representative software, Helmholtz energy EOS is installed and all the thermodynamic properties can be calculated easily. However, the accuracy and reliability of the calculated values depend on the measured data which are used to build the EOS.

Transport properties which are thermal conductivity and viscosity can also be calculated by the REFPROP. When sufficient accurate data exist and a correlation is established for a refrigerant, the correlation is used and reliable values are obtained. When measured data do not exist for a refrigerant, the extended corresponding state model [7, 8] is used to estimate properties. However, the uncertainty of the estimation is somewhat large which is stated in REFPROP as 20%. In case there are some data though they are not sufficient numbers, fitting parameters are introduced in the ECS model and more reliable values can be calculated.

As an example, an effect of viscosity estimation is explained here. Fig.1 shows comparison of viscosity values of R1233zd(E) [9]. One group is experimentally measured values and another is estimated values by REFPROP ver.9.1 [10] which is a previous version. The measured viscosity has around 25 % to 37 % lower value than the estimated viscosity.

In Fig.3, measured condensation heat transfer coefficients of R1233zd(E) on a horizontal tube are compared with predicted heat transfer coefficients calculated by the Nusselt theory [11]. When this measurement was carried out, thermophysical properties of R1233zd(E) were not sufficiently clarified and the experimental data had around 25 % higher value than the Nusselt theory. On the other hand, the Nusselt theory calculated by using measured viscosity [9] shows better agreement with the experimental data. Although the results are not shown here, experimental heat transfer coefficients of R1234ze(E) and R1234ze(Z) agreed well with the Nusselt theory [11]. This result indicates that the reliability of measured viscosity and importance of accurate thermophysical properties.

When we evaluate new refrigerant performance, which are heat transfer, cycle simulation, drop-in test, etc., reliabilities of each property should be confirmed. Even widely used software such as REFPROP, calculated values are not fully reliable.

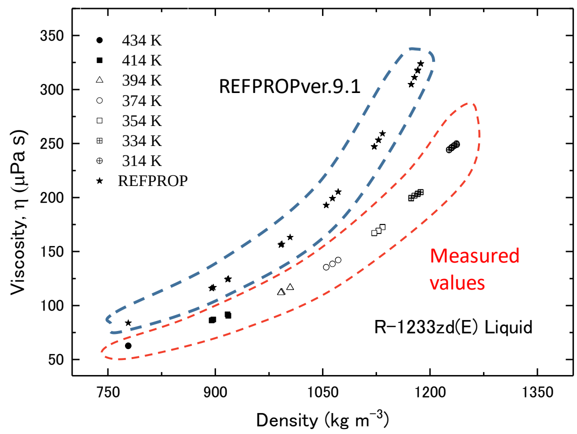

Fig.2 Measured viscosity of liquid R1233zd(E) and calculated value with REFPROP ver.9.1

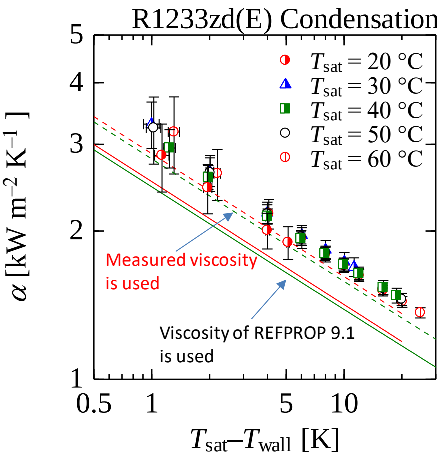

Fig.3 Measured condensation heat transfer coefficient and Nusselt theory of R1233zd(E) on a horizontal tube

5. Efficient use of new refrigerants

As shown in Table 1, most of the new refrigerants are zeotropic refrigerant mixtures in which temperature changes during condensation and evaporation processes in heat exchangers and heat transfer degraded. These characteristics have been previously revealed.

Figs.4 (a) and (b) show experimental values and simulation results on the temperature change of refrigerant and water in heat exchangers [12]. Although refrigerants used were R22 and R22+R114 mixture which have phased out because of ozone layer depletion problem, new refrigerant mixtures will also show similar behaviors. In this case, counter current type heat exchangers were used and quasi-parallel temperature differences between refrigerant and water were achieved for refrigerant mixture. The experiment was conducted under a condition of a heat pump system. The heat output was 1.98 kW, inlet and outlet temperatures of heated water in the condenser were around 30 °C and 50 °C and inlet temperature in the evaporator was around 20 °C. The heat pump system was operated to satisfy the above conditions and state points of refrigerants were measured. The cycle simulation was conducted by using correlations of heat transfer and pressure losses. The simulated cycles of both R22 and R22+R114 agree well with the experimental results.

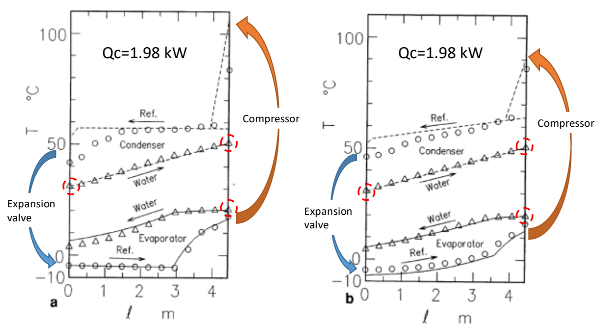

Fig.4 Temperature change of refrigerant and water in condenser and evaporator of a heat pump

The parallel temperature differences are expected to reduce irreversible losses in the heat exchangers and improve the coefficient of performance (COP) of the heat pump cycle. However, heat transfer degradation of the mixture prevents the improvement of COP. Fig.5 indicates the relation between COP and mass fraction of mixture with a parameter of heat transfer length. The solid lines are calculated results in which pressure loss is ignored. The dashed lines are results including the effect of pressure loss. Increasing the heat transfer length achieves improvement of COP. However, at the same time, the pressure loss also increases and the COP decreases. This is more remarkable in low pressure mixture with low R22 mass fraction. By using a multi-path heat exchanger, the increase of pressure loss and the decrease of COP might be avoided. Although the effect of mass fraction is weak, there are maximum peak in the long heat transfer tube and minimum peak in the short tube.

Appropriate design and simulation of refrigeration systems in which a new refrigerant mixture is used are expected.

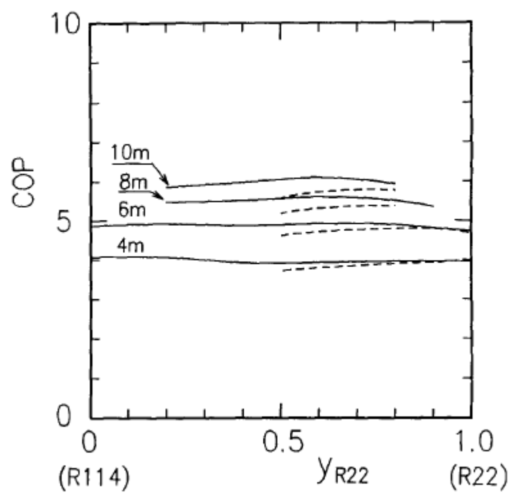

Fig.5 Effects of tube length on the change of COP with mass fraction

A series of comparative experimental studies on heat pump cycle using new refrigerants mixtures were conducted by Koyama et al. [13, 14]. Fig.6 shows the experimental apparatus which is a simple vapor compression heat pump system. Water cooled condenser and water heated evaporator were used and experiments were carried out by giving heating or cooling capacity as an operating condition of heat pump or refrigeration system, respectively. Degree of superheat at evaporator exit was kept as 3 K to 4.5 K.

Koyama et al. [13, 14] conducted the experiments on both heating mode and cooling mode. Heating or cooling output was varied as an operating parameter and temperatures of water inlet and outlet of condenser and evaporator were fixed as experimental conditions. Although they tested two conditions of heating mode and one condition of cooling mode, only the heating mode is explained here. The experimental result is shown in Fig.7. The condenser inlet and outlet temperatures were 20 °C and 45 °C. Evaporator inlet and outlet were 15 °C to 9 °C. Heating output was varied from 1.6 kW to 2.8 kW. Tested refrigerants are binary mixtures, R32+R1234ze(E), R32+R1234yf, ternary mixtures, R744+R32+R1234ze(E), R744+R32+R1234yf, and currently used refrigerants, R410A, R32. As shown in Fig.7, there are refrigerant mixtures which have higher COP than R410A. The 42mass%R32+58%mass%R1234ze(E) and the 4mass% R744+43mass%R32+53mass%R1234ze(E) have the highest COP though the COP of R32 is higher in the range of Q_{COND}>2.2 kW. This result indicates that there is a possibility finding a suitable refrigerant mixture under a given operation condition. Additionally, ODP, GWP, flammability and toxicity also need to be taken in to account for practical use.

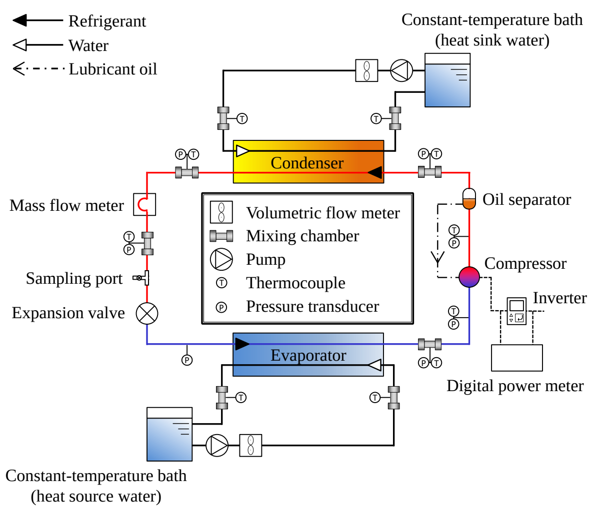

Fig.6 Experimental apparatus of heat pump cycle used by Koyama et al. [13, 14]

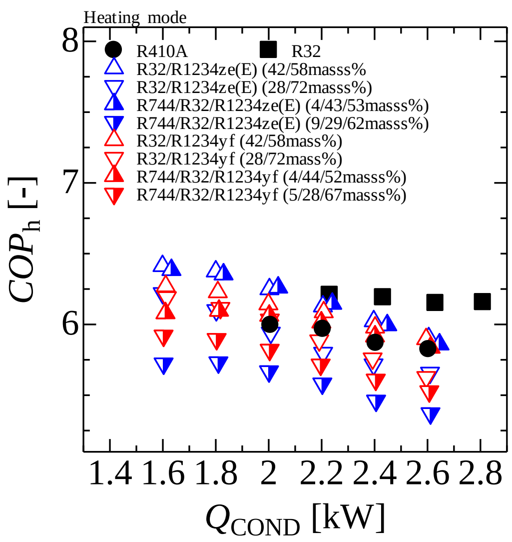

Fig.7 Relation between COP and heat output by Koyama et al. [13, 14]

Fig.8 shows ratios of irreversible loss and heat output of each component which are the condenser, evaporator, expansion valve, compressor, piping and pressure drop. Because the irreversible loss leads to the COP degradation and allows to compare the effects of each component with same scale, the comprehensive evaluation can be conducted. Irreversible losses of compressor and condenser are larger than other components. Therefore, improving the compressor and condenser is important. And it can be also understood that the lowest COP of 9mass%R744+29mass%R32 +62mass%R1234ze(E) is caused by larger irreversible losses of evaporator and expansion valve than other refrigerants.

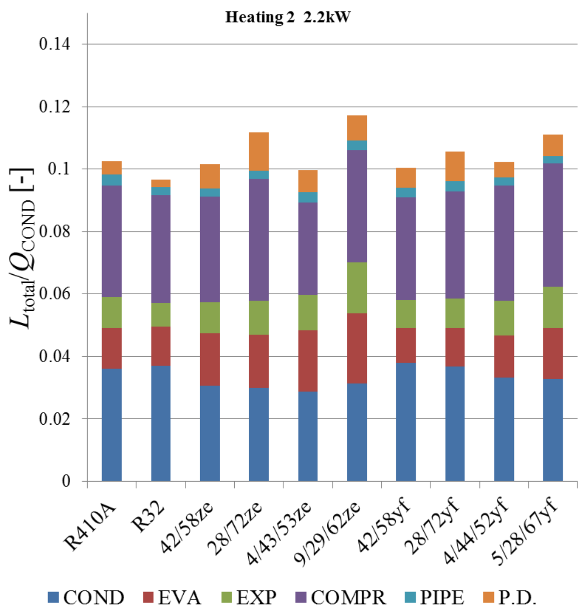

Fig.8 Irreversible losses of condenser, evaporator, expansion valve, compressor, piping, pressure drop in heat exchangers. [13, 14]

6. Refrigerant management

In midway of 3rd generation to 4th generation and even if the 4th generation refrigerants have been developed successfully, current refrigerants and drop-in refrigerants will be transiently used in current systems. Therefore, the refrigerant management is needed. In some countries, a law for refrigerant management is in place. However, the management ways which are not covered yet in the law should be considered for the smooth refrigerant transition. Regular inspection of refrigerant leakage and prompt repair when the leakage is detected are necessary. Although refrigerant recovery and recycle have been started, the recovery rate is not sufficient and many refrigerants are released in the atmosphere and some of recovered refrigerants are destroyed without recycle. Appropriate purification process of recovered refrigerants and quality assurance are needed.

7. Conclusions

In the history of refrigeration and air-conditioning, the transition to fourth-generation refrigerants is the biggest revolution to achieve the evolution of sustainable refrigeration and air-conditioning systems. Although some new refrigerants have been proposed, issues of GWP and flammability of the refrigerants have not been solved sufficiently yet. Further studies are required on thermophysical properties, heat transfer, and system evaluation. And, suitable refrigerants should be selected for each system with different temperature ranges, capacities, usage places/conditions.

8. Acknowledgement

First of all, I would like to express my sincere gratitude to Professor Koyama, who passed away on August 4, 2018, for his valuable suggestions and encouragement in this study. Many parts of the research reported in this manuscript are financially supported by projects of the New Energy and Industrial Technology Development Organization (NEDO), Japan.

8. References

[1] Calm, J.M., The next generation of refrigerants – Historical review, considerations, and outlook, International Journal of Refrigeration, vol. 31, pp. 1123-1133, 2008.

[2] McLinden, M.O., Thermodynamics of the new refrigerants, Proceedings of the 25th International Congress of Refrigeration, International Institute of Refrigeration, Montreal, Canada, ID:1746, 2019.

[3] Miyara, A., Onaka, Y., Koyama, S., Ways of next generation of refrigerants and heat pump/refrigeration systems, International Journal of Air-Conditioning and Refrigeration, vol. 20, 1130002, 2012.

[4] McLinden, M.O., Huber, M.L., (R)Evolution of refrigerants, Journal of Chemical Engineering Data, vol. 65, pp. 4176-4193, 2020.

[5] https://www.ashrae.org/technical-resources/standards-and-guidelines/ashrae-refrigerant-designations (November, 2020)

[6] Lemmon, E.W., Bell, I.H., Huber, M.L., McLinden, M.O., NIST Standard Reference Database 23, NIST Reference Fluid Thermodynamic and Transport Properties, version 10.0, Standard Reference Data Program, National Institute of Standards and Technology, Gaithersburg, MD, 2018.

[7] Huber, M.L., Ely, J.F., A predictive extended corresponding state model for pure and mixed refrigerants including an equation of state for R134a International Journal Refrigeration, vol. 17, pp. 18-31, 1994.

[8] Klein, S.A., McLinden, M.O., Lasecke, A., An improved extended corresponding state method for estimation of viscosity of pure refrigerants and mixtures, International Journal of Refrigeration, vol. 20, pp. 208-217, 2000.

[9] Miyara, A., Alam, Md.J., Kariya, K., Measurement of viscosity of trans-1-chloro-3,3,3-trifluoropropene (R-1233zd(E)) by tandem capillary tubes method, International Journal of Refrigeration, vol. 92, pp. 86-93, 2018.

[10] Lemon, E.W., Huber, M.L., McLinden, M.O., NIST Standard Reference Database 23, Reference fluid Thermodynamic and Transport Properties (REFPROP), version 9.1, National Institute of Standards and Technology, Gaithersburg, MD., 2015.

[11] Nagata, R., Kondou, C., Koyama, S., Comparative assessment of condensation and pool boiling heat transfer on horizontal plain single tubes for R1234ze(E), R1234ze(Z), and R1233zd(E), International Journal of Refrigeration, vil. 63, pp. 157-170, 2016.

[12] Miyara, A., Koyama, S., Fujii, T., Performance evaluation of a heat pump cycle using NARMs by a simulation with equations of heat transfer and pressure drop, International Journal of Refrigeration, vol. 16, pp. 161-168, 1993.

[13] Kojima, H., Aragaki, S., Fukuda, S., Takata, N., Kondou, C., Koyama, S., Comparative study on heat pump cycle using R32/R1234yf and R744/R32/R1234yf mixtures, Proceedings of the 8th Asian Conference on Refrigeration and Air Conditioning, Taipei, Taiwan, ACRA2016-105, 2016.

[14] Koyama, S., https://www.nedo.go.jp/content/100765864.pdf (Nov., 2020)

ICMIEE20-KN03

Tires, Tires, Tires Everywhere – What Shall We Do? An Entrepreneurial Thinking and Innovation Model

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ABSTRACT
The challenge of engaging students in the learning process has been a topic of educators around the globe. The opportunity to engage students through student-based and active and collaborative learning continues to offer great promise in meeting this challenge. The creation of an exercise that engages the student demonstrates that Problem Based Learning outcomes can be an effective approach to delivering meaningful engineering education content. This presentation will focus on the utilization of Problem Based Learning as a vehicle that fosters student- based learning as a key ingredient to engage the learner. Students learn differently! The implementation of Problem Based Learning in the engineering discipline has proven to be a viable approach to harnessing the student's curiosity and desire to explore. The Tires, Tires, Tires Everywhere exercise relies on the collaboration of student groups to address a systemic societal environmental problem. It further enables the student to express the solution in economic terms while applying business model thinking. The level of learning that occurs in utilizing the project based interactive exercises with global and societal issues is worth examining as a viable tool in engineering education. Problem Based Learning exercises that apply to solving real-world problems appeal to engineering students.

Keywords: Entrepreneurship, Innovation, Sustainability, Experiential Learning and Problem Solving.

ICMIEE20-KN04

Recent and Ongoing Advancements in Research on Magnetic Suspension

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ABSTRACT

Magnetic suspension maintains an object (floator) in space with no visible means by magnetic force. No mechanical friction is expected in operation even without lubrication. This advantage has already given rise to a lot of industrial applications such as Maglev system, and active magnetic bearing for complete contact-free suspension of rotating object.

Researches and developments on magnetic suspension have been actively pursued for several decades and some people may consider this technology to be rather mature now. However, to fully utilize this unique technology and to increase industrial applications, technical advances are still important.

This report presents several recent innovations and advances in magnetic suspension technology. An overview of technological fundamentals is presented first, which is followed by reports on the recent and ongoing works conducted in the author's laboratory.

Keywords: Magnetic suspension, Magnetic Bearing, Mechatronics, Electromagnet, Permanent magnet

ICMIEE20-KN05

Bioinspired Electrospun Nanocomposites: An Emerging Technology of Atmospheric Fog Water Generator

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ABSTRACT

Nature-inspired fog harvesting is a promising technology aimed at acquiring freshwater from the atmosphere. However, the design of nature-inspired surfaces with unique characteristics for this specific application provides a paradigm shift in the development of the new engineering surfaces. Efficient fog collecting nanofibers were designed with the inspiration of fog-harvesting capability of Stenocara beetles in the Namib Desert. Several available polymers such as polyacrylonitrile (PAN), polymethyl methacrylate (PMMA), recycled expanded polystyrene (EPS) foam with various proportions of titanium dioxide (TiO_2) nanoparticles, and aluminum (Al) microparticles were spun into superhydrophobic-hydrophilic nanocomposite fibers using the facile electrospinning technique. The fiber morphology, wetting characteristics, and fog-harvesting capacity of the nanocomposites were investigated. The as-prepared PAN/PMMA and EPS nanocomposites having 10% inclusion of combined micro-and nanoparticles exhibit superhydrophobic characteristics i.e. a water contact angle of 154.8° and 152.03° respectively. The experimental tests of PAN/PMMA and EPS nanocomposites reveal the daily freshwater productivity of more than 1.49 liter/m^2 and 1.35 liter/m^2 of nanocomposites. The cost of materials formaking such nanocomposites to supply estimated daily water consumption for a household with 2 members (i.e., 6 liters) is only US$2.67 (EPS nanocomposite) and US$4.97 (PAN/PMMA nanocomposite). These nanocomposites harvest fog water without any additional energy input or any large infrastructure thus, it's cheap and affordable. This technology offers a novel and very cost effective tool for the production of freshwater in arid areas.

Keywords: Electrospinning, carbonization, superhydrophobicity, fog water generator.

1. Introduction

The global water shortage problem has given rise to the evolution of water-capturing technology since the 20th century, particularly in arid and semi-arid countries. However, atmospheric fog can account for a considerable number of freshwater sources. The atmosphere holds 37.5 million billion gallons of water in the invisible vapor phase [1]. The United Nations Convention to Combat Desertification reports that by 2025 about 2.4 billion people will suffer from water scarcity [2]. Hence, engineers and scientists are confronted with discovering economically suitable and applicable water resources to solve the problem. In some countries, possible systems include rain and groundwater harvesting. The cloud seeding is also used in some locations. These systems typically produce clean water for drinking, agriculture, medical, and other purposes [3]. Harvesting fog water with high efficiency is an attractive proposal to relieve the risk of water shortage [4].

In nature, many animals and plants have special surface wetting characteristics designed with a combination of micro-and nanoscale structures [5-11]. For example, the Stenocara beetle harvests water instantly from the fog and mist. This beetle's carapace has a combination of hydrophilic bumps and a hydrophobic surface. These hydrophilic bumps capture the fog droplet, carried by wind and coalescence, and then the hydrophobic surface directs the water straight to the beetle's mouth [12]. Cribellate spiders utilize silk with spindle-knots and a joint structure that allows wettability and curvature gradients to capture water from the atmosphere [5]. Only a few studies have considered the fabrication of superhydrophobic polymeric nanocomposite fibers for water harvesting using nanotechnology [13]. Wang et al. fabricated the hydrophilic-superhydrophobic surface for efficient fog collection in 2015. The hybrid surface is produced with superhydrophobic structure transformed metal-based gauze bonded to the surface of the hydrophilic polystyrene (PS) flat sheet. The hydrophilic-superhydrophobic designed hybrid surface obtained a high collection capacity of 159 mg/cm^2/h [14].

In another study, fourteen polyethylene terephthalate (PET) fibers with individual cross-sections and surface structures such as microgrooves were fabricated, and fog collection efficiency was measured. It was witnessed that micro-grooved fiber surfaces rise depositing efficiency and enhance drainage efficiency [15]. Almasian et al. fabricated fluorinated superhydrophobic PAN nanofibers for studying their fog-harvesting properties. The fabrication method was optimized by variable temperature, time, and quantity of fluoroamine compound. Fabricated PAN nanofibers showed a water contact angle of 159° and a low surface energy of 17.1 mN/m. The highest fog-harvesting capacity of 335 mg/cm^2.hr was attained when the nanofibers were dried for 3 hr at 95°C, and the quantity of fluoroamine compound was 8% (w/w) in the process [16]. Even though plenty of methods have been established to resemble the structure on Stenocara beetles' back for water-harvesting, however, places, where peoples are suffering for water, is poverty-stricken and underdeveloped regions, where materials and manufacturing services are insufficient [17-18]. Hence, simple fabrication, mass production, and handling of fog water harvesting materials remain as issues to be solved for wide application of this new technology. Our study

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focuses on fabricating superhydrophobic-hydrophilic nanocomposite fibers via electrospinning using two types of polymers, namely PAN/PMMA and waste EPS foam with the introduction of TiO_2 nanoparticles and Al microparticles. Thesurface wetting characteristics, morphology of fibers, and fog water harvesting performance were studied.

2. Experimental Setup

2.1 Materials

PAN (molecular weight, Mw 150,000 g/mole, Tg 95°C) and PMMA (Mw 120,000 g/mole, Tg 99.0°C) were purchased from Sigma-Aldrich (St. Louis, MO, USA). The waste EPS was collected from the packaging of laboratory chemicals. TiO_2 nanoparticles of average particle size of 40 nm (anatase, 99.5%) and Al microparticles (99.7%, 10 μm) were both purchased from U.S. Research Nanomaterials Inc., TX, USA. All materials used in this study were original without any modifications to the supplier specifications.

2.2 Fabrication of Polymer Nanocomposite

The nanocomposite fibers using two types of polymers were fabricated using the facile electrospinning method. Both types of polymers were dissolved in DMF at a ratio of 80:20 at 45°C and stirred for 2 h to obtain a homogeneous polymeric solution. The ratio of PAN and PMMA was 25:75 percent by weight. Different concentrations of micro-and nanoparticles were used (0, 2.5, 5, and 10 wt%) to fabricate the nanocomposite fibers which were added into the polymer solution and stirred for another 2 h, followed by 20 min of probe sonication to produce a homogeneous polymer solution. The prepared solution was electrospun and then dried for 24 h in an open atmosphere. The electrospinning was conducted at 25 kV, and a feed rate of 1 ml/h and the distance between the tip and collector was 25 cm. The fabricated nanocomposite fibers were then stabilized and carbonized at 250°C and 850°C for 1 h in an oxygen and argon environment respectively to separate the entire remnant solvent and retained moisture. The electrospinning procedure limits were held steady for each type of polymers produced in the study. Fig. 1 demonstrates a step-by-step demonstration of the fabrication process of electrospun nanocomposite fibers.

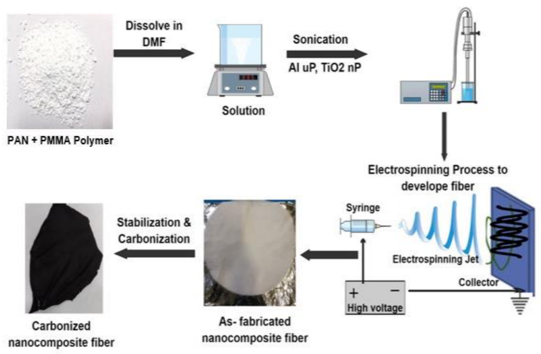

Fig. 1 Illustration of the fabrication process of electrospun nanocomposite fibers.

2.3 Characterization of Nanocomposite Fibers

The wetting characteristics of the nanocomposites were measured with a water contact angle goniometer (KSV Instruments Ltd., Model #CAM 100). A scanning electron microscopy (SEM) (FEI Nova Nano SEM 450) was used to study the morphology of the nanocomposites. The surface roughness was measured by a Mitsutoyo 178-561-02A Surftest SJ-210 Surface Roughness Tester. Over a range of 3500−500 cm^{-1}, the surface chemistry of the nanocomposite fibers was achieved by Fourier-transform infrared spectroscopy (FTIR) (Thermo Scientific™ Nicolet™ iN10 infrared microscope).

3. Results and Discussion

3.1 Characteristics of Nanocomposite

Fig. 2 displays the FTIR spectra of the carbonized PAN/PMMA nanocomposite. The PAN molecule is a sequential arrangement of methyl (CH_3) and nitrile (C≡N) groups [19]. However, when the carbonization process occurs at a high temperature of 850°C, entire volatile compounds are burnt out, which leaves only carbon and hydrogen molecules in the carbon fiber structure. The peak intensities at 987 and 1450 cm^{-1} are given to the aliphatic CH group vibration of various modes in CH_2 and CH correspondingly in the spectrum of untreated fiber. The bands corresponding to 1150 and 1720 cm^{-1} are because of C-O and C=O stretching, and the bands corresponding to 1240 and 2360 cm^{-1} are C-N and C≡N stretching. The absorption peaks of C-O and C=O groups deteriorate slowly with the accumulation of Al microparticles and TiO_2 nanoparticles. Most significantly, all the strong peaks vanished after carbonization. The intensity bands at all peaks vanished, compared to the untreated PAN/ PMMA fibers spectrum.

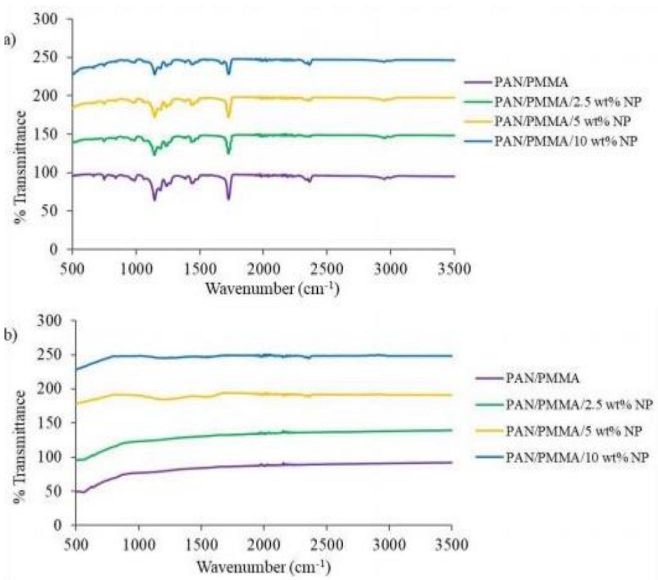

Fig. 2 FTIR spectra of nanocomposite fibers: (a) as prepared and (b) after carbonization.

The average roughness of the as-prepared PAN/PMMA nanocomposite fibers showed 0.34±0.02 μm, and it was influenced substantially due to the introduction of micro and nanomaterials. For 2.5, 5, and 10 wt.% inclusions of micro and nanomaterials, the average roughness of the PAN/PMMA nanocomposite fiber were 0.49±0.03, 0.94±0.05, and 1.77±0.04 µm respectively. However, EPS nanocomposite with 0 wt% micro and nanomaterials showed the roughness of 0.78±0.03 µm. For 5, 10, and 15 wt% inclusions of micro and nanomaterials, the average roughness of the EPS nanocomposite was 1.35±0.02, 1.81±0.04, and 2.55±0.05 µm, respectively, as shown in Table 1. Various chemical stimulations, including degradation, cross-linking, and cyclization, can happen due to the high-temperature heat treatment of the PAN/PMMA nanocomposite. The mechanism of the process is based on the polymer and type, inclusion percentage, and heating rate [20].

Table 1 The average roughness of various nanocomposites.

Nanocomposite	Average Roughness (Ra, µm)	Nanocomposite	Average Roughness (Ra, µm)
PAN/PMMA	0.34±0.02	EPS	0.78±0.03
PAN/PMMA/2.5 wt% NP	0.49±0.03	EPS/5 wt% NP	1.35±0.02
PAN/PMMA/5 wt% NP	0.94±0.05	EPS/10 wt% NP	1.81±0.04
PAN/PMMA/10 wt% NP	1.77±0.04	EPS/15 wt% NP	2.55±0.05

Fig. 3 presents the SEM images of the PAN/PMMA nanocomposite. As shown in Fig. 3(a), the fibers were noticed significantly fewer beading structures with uniform diameters and smooth surfaces. Fig. 3**Error! Reference source not found.**(c) illustrates the nanocomposite fabricated with an inclusion of 10 wt% of Al and TiO_2 nanoparticles. As the nanoparticle reinforcement increases, the beading and agglomeration of the structure increase, and rough surfaces were produced. Viscosity, conductivity, elasticity, and surface tension of the solution significantly impact the transformation of the polymer solution into nanocomposite.

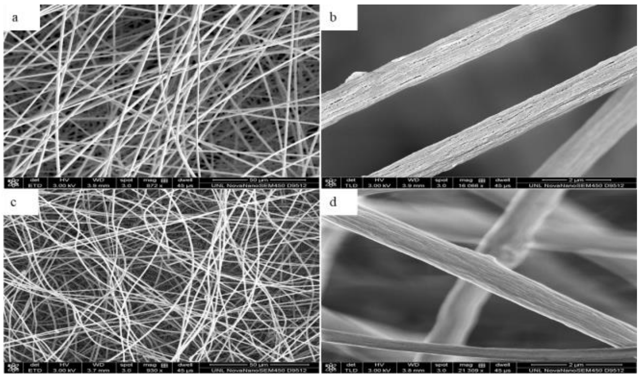

Fig. 3 SEM images of PAN/PMMA nanocomposites with micro and nanomaterials reinforcement at low and high magnification; (a, b) 0 wt% NP and (c, d) 10 wt% NP.

3.2 Wetting Characteristics of Nanocomposite

The average water contact angle of carbonized PAN/PMMA nanocomposite without any inclusion of nanoparticles was 130.88°, and with 10wt% nanoparticles was 154.8°. The maximum average water contact angle of 152.03° was noted for EPS nanocomposite with 10 wt% nanoparticle inclusions. Consequently, the carbonized nanocomposite with 10 wt% inclusions of nano- and microparticles reveal the superhydrophobic property. The water contact angle of the different nanocomposites is summarized in Table 2.

Table 2 The water contact angle of various nanocomposites with Al microparticles and TiO_2 nanoparticles.

Nanocomposite	Water contact angle (º)	Nanocomposite	Water contact angle (º)
PAN/PMMA	130.88±2.43	EPS	116.29±2.75
PAN/PMMA+2.5 wt.% NP	141.62±1.97	EPS/5 wt.% NP	131.99±2.34
PAN/PMMA+5 wt.% NP	149.73±1.34	EPS/10 wt.% NP	152.03±3.16
PAN/PMMA+10 wt.% NP	154.80±3.02	EPS/15 wt.% NP	143.60±2.64

The formation of a ladder-like structure of PAN was developed while stabilizing the nanocomposite at 280°C in an oxygen environment. The primary purpose of the stabilization process during the fabrication is to chemically, physically, and thermally stabilize the nanocomposite fibers, which is a significant factor for superhydrophobicity. Moreover, the nanocomposite is modified from thermoplastic to thermosetting during the stabilization process, which decreases the diameter and changes the color. However, in the carbonization process, the nanocomposite fibers heated at 850°C in an argon environment led to the transformation of nanocomposite fibers into carbon fibers. During this process, PMMA is burned out, leaving porous fibers, and releases the radicals which adhered to the primary chain of the nanocomposite fiber to eliminate the polarity. The surface roughness and porosity generate a noticeable heterogeneous wettability in which the air is entrapped by water in the surface cavities [21-22], which provides less contact area between the water and the solid substrate while improving the contact area between the water and the air, which leads to an increment of wettability of the surface.

3.3 Fog Harvesting Performance of Nanocomposite

The prominent mechanisms that affect fog-harvesting efficiency include capturing, collecting, and transporting. In the capturing phase, the fabricated surface must capture the tiny fog water droplets moving with the flowing air [23]. The harvesting efficiency is subject to the airflow velocity and hydrophilicity of the fabricated surfaces [24]. The collecting phase is vital for a fabricated surface to achieve high efficiency, which can reduce due to evaporation of fog water droplets in massive airflow. Lastly, in the transporting phase, the fog water droplets roll off the fabricated surface as they grow large enough to break out. The surface area along with the hydrophobicity with the tilted angle significantly influence this phase. All these three phases should be fast enough to reduce evaporation and improve harvesting efficiency. In this study, the fog harvesting performance of PAN/PMMA and EPS nanocomposites were tested by using a tabletop unit. A conventional ultrasonic humidifier was utilized to generate the artificial fog. The humidifier operated with a fog flow velocity of 330 ml/h. The fog collection performance of the nanocomposites were experimented under the temperature and humidity maintained at 19±2°C and 68±3%, respectively. The nanocomposite was located vertically intersecting the fog flow direction. The harvested water by the nanocomposite was collected using a beaker and recorded every 20 min for 60 min. The results of the fog harvesting capacity of two different nanocomposites are presented in Table 3. The nanocomposites with 10 wt% of micro-and nanoparticles exhibited greatest water collecting performance.

Table 3 The fog harvesting capacity of various nanocomposites.

Nanocomposite	Fog harvesting capacity ($gm/cm^2/h$)	Nanocomposite	Fog harvesting capacity ($gm/cm^2/h$)
PAN/PMMA	0.258±0.021	EPS	0.236±0.026
PAN/PMMA/2.5 wt% NP	0.411±0.018	EPS/5 wt% NP	0.468±0.016
PAN/PMMA/5 wt% NP	0.507±0.027	EPS/10 wt% NP	0.561±0.033
PAN/PMMA/10 wt% NP	0.621±0.023	EPS/15 wt% NP	0.387±0.019

The PAN/PMMA nanocomposite without any inclusion of nanoparticles revealed a fog harvesting capacity of 0.258 $gm/cm^2/h$. The highest fog harvesting capacity among all four different PAN/PMMA nanocomposite was 0.621 $gm/cm^2/h$, which is PAN/PMMA with 10 wt% micro-and nanoparticles sample. The EPS nanocomposite without any inclusion of nanoparticles also exhibited the fog harvesting capacity of 0.236 $gm/cm^2/h$, whereas, with the introduction of 5 and 10 wt % micro-and nanoparticles, the fog harvesting capacities rise to 0.468 and 0.561 $gm/cm^2/h$ respectively.

The hydrophilic characteristics of TiO_2 nanoparticles and Al microparticles ameliorate the fog harvesting performance substantially when combined with a superhydrophobic domain. The inclusions of TiO_2 nanoparticles and Al microparticles enhance the water coalescence and condensation process on those surfaces with superhydrophobic domains. The superhydrophobic-hydrophilic hybrid surface validates the superior fog harvesting capacity. Furthermore, the tiny fog water droplets that are captured on the hydrophilic sections typically move toward the hydrophobic sections due to the wettability properties [25]. The collective outcome of the hydrophobic surface with several hydrophilic sites dominate the fog harvesting capacity of the nanocomposite. An efficient fog harvesting nanocomposite must have enough hydrophilic sites to capture and collect the fog water droplets. Accordingly, the nanocomposite with the inclusion of micro-and nanoparticles enhances the surface water droplet coalescence and drainage, which are two challenging progressions in fog harvesting.

4. Conclusions

We developed a simple and affordable fabrication method of superhydrophobic-hydrophilic nanocomposite from PAN/PMMA and waste EPS that offers greater fog harvesting performance. The carbonized PAN/PMMA nanocomposite with 10 wt% nanoparticles inclusion shows superhydrophobic characteristics (water contact angle 154.8°) and daily water productivity greater than 1.49 liter/m^2 of the nanocomposite. Similarly, the EPS nanocomposites with 10 wt% nanoparticles inclusion also show superhydrophobic characteristics (water contact angle 152.03°) and daily water productivity of more than 1.35 liter/m^2. It is estimated that the materials cost of producing EPS and PAN/PMMA nanocomposites to supply minimum daily water consumption for a household of 2 members is only US$2.67 and US$4.97 respectively. Due to higher fog harvesting capacity and usage durability, the established technology has enormous practical value in large-scale applications. The experimental results show that uniform diameter fibers were produced. It is more reliable to conclude that this technology has potential applications to harvest fog water on a large scale in water-deficient countries.

References

1. Onda, K., Lobuglio, J. & Bartram, J, Global access to safe water: Accounting for water quality and the resulting impact on MDG progress, International Journal of Environmental Research and Public Health, vol. 9, pp. 880–894, 2012.
2. Dooley, E. E., United nations convention to combat desertification. *Environmental Health Perspectives*, vol. 110, 2002. https://www.unccd.int/Sites/Default/Files/Documents/12112014_Invisible%0AFrontline_ENG.Pdf.
3. Uddin, M. N., Alamir, M., Muppalla, H., Rahman, M. M. & Asmatulu, R, Nanomembranes for Sustainable Fresh Water Production, in The 5th *International Conference on Mechanical, Industrial and Energy Engineering* pp. 23–24, 2018.
4. Qadir, M., Jiménez, G. C., Farnum, R. L., Dodson, L. L. & Smakhtin, V., Fog water collection: Challenges beyond technology.

Water (Switzerland), vol. 10, pp. 372, 2018.

5. Zheng, Y., Bai, H., Huang, Z., Tian, X., Nie, F.Q., Zhao, Y. Zhai, J., Jiang, L., Directional water collection on wetted spider silk, *Nature*, vol. 463, pp. 640–643, 2010.
6. Uddin, M. N., Desai, F. J., Rahman, M. M. & Asmatulu, R. Highly Efficient Fog Harvester of Electrospun Permanent Superhydrophobic-Hydrophilic Polymeric Nanocomposite Fiber Mats. *Nanoscale Advances,* Nanoscale Advances, vol. 2, pp. 4627-4638, 2020.
7. Uddin, M. N., Desai, F. J. & Asmatulu, E, Biomimetic electrospun nanocomposite fibers from recycled polystyrene foams exhibiting superhydrophobicity, *Energy, Ecology and. Environment*, vol, 5, pp. 1–11, 2020.
8. Salahuddin, M., Uddin, M. N., Hwang, G. & Asmatulu, R., Superhydrophobic PAN nanofibers for gas diffusion layers of proton exchange membrane fuel cells for cathodic water management, *International Journal of Hydrogen Energy*, vol. 43, pp. 11530–11538 2018.
9. Uddin, M. N., Rahman, M. M. & Asmatulu, R. Efficient fog harvesting through electrospun superhydrophobic polyacrylonitrile nanocomposite fiber mats, in Proc. SPIE *Bioinspiration, Biomimetics, and Bioreplication X,* vol. 11374, 31, 2020.
10. Uddin, M. N., Rahman, M. M. & Asmatulu, E. Sustainable freshwater harvesting from atmosphere through nanocomposite fibers of recycled polystyrene foams, in Proc. SPIE *Behavior and Mechanics of Multifunctional Materials IX*, vol. 11377, 52, 2020.
11. Jurak, S. F., Jurak, E. F., Uddin, M. N. & Asmatulu, R., Functional superhydrophobic coating systems for possible corrosion mitigation, *International Journal of Automation Technology*, vol. 14, pp.148–158, 2020.
12. Parker, A. R. & Lawrence, C. R., Water capture by a desert beetle, *Nature*, vol. 414, pp. 33–34 2001.
13. Subeshan, B., Usta, A. & Asmatulu, R. Deicing and self-cleaning of plasma-treated superhydrophobic coatings on the surface of aluminum alloy sheets, *Surfaces and Interfaces*, vol. 18, pp. 23105, 2020.
14. Wang, Y., Zhang, L., Wu, J., Hedhili, M. N. & Wang, P., A facile strategy for the fabrication of a bioinspired hydrophilic-superhydrophobic patterned surface for highly efficient fog-harvesting, *Journal of Material Chemistry A*, vol. 3, pp. 18963–18969, 2015.
15. Azad, M. A. K., Krause, T., Danter, L., Baars, A., Koch, K. & Barthlott, W., Fog Collection on Polyethylene Terephthalate (PET) Fibers: Influence of Cross Section and Surface Structure, *Langmuir*, vol. 33, pp. 5555–5564, 2017.
16. Almasian, A., Chizari Fard, G., Mirjalili, M. & Parvinzadeh Gashti, M., Fluorinated-PAN nanofibers: Preparation, optimization, characterization and fog harvesting property, *Journal of Industrial and Engineering Chemistry,* vol. 62, pp. 146–155, 2018.
17. Asmatulu, E., Subeshan, B., Twomey, J. & Overcash, M., Increasing the lifetime of products by nanomaterial inclusions—life cycle energy implications, *International Journal of Life Cycle Assessment,* 2020. doi:10.1007/s11367-020-01794-w.
18. Lei, J. & Guo, Z., A fog-collecting surface mimicking the Namib beetle: Its water collection efficiency and influencing factors, *Nanoscale, vol.* 12, pp. 6921–6936, 2020.
19. Saufi, S. M. & Ismail, A. F., Development and characterization of polyacrylonitrile (PAN) based carbon hollow fiber membrane, *Songklanakarin Journal of Science and Technology*, vol. pp. 24, 843–854, 2002.
20. Goracheva, V. O., Mikhailova, T. K., Fedorkina, S. G., Konnova, N. F. Azarova, M. T., Konkin, A. A., Thermographic and thermogravimetric analysis of the thermal behaviour of polyacrylonitrile fibres, Fibre Chemistry, vol. 5, pp. 496–498, 1974.
21. Sas, I., Gorga, R. E., Joines, J. A. & Thoney, K. A., Literature review on superhydrophobic self-cleaning surfaces produced by electrospinning. *Journal of Polymer Science Part B: Polymer Physics, vol.* 50, pp. 824–845, 2012.
22. Alexander, T., Subeshan, B. & Asmatulu, R., Modifying the figure of merit of thermoelectric materials with inclusions of porous structures. *Energy, Ecology and Environment*, vol. 5, pp. 313–329, 2020.
23. Thickett, S. C., Neto, C. & Harris, A. T., Biomimetic surface coatings for atmospheric water capture prepared by dewetting of polymer films, *Advanced Materials,* vol. 23, pp. 3718–3722, 2011.
24. Andrews, H. G., Eccles, E. A., Schofield, W. C. E. & Badyal, J. P. S., Three-dimensional hierarchical structures for fog harvesting, *Langmuir,* vol. 27, pp. 3798–3802, 2011.
25. Lee, A., Moon, M. W., Lim, H., Kim, W. D. & Kim, H. Y., Water harvest via dewing. *Langmuir, vol.* 28, pp. 10183–10191, 2012.

ICMIEE20-KN06

Energy security, nuclear power generation and human resource development

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ABSTRACT

The quest for clean energy in power generation necessitates to look for nuclear energy for power generation to reduce our absolute dependency on fossil fuel. Currently over 50 countries from Asia, Africa and South America are considering nuclear energy for power generation due to its numerous advantages compared to fossil fuels and renewables. Furthermore, globally 48 nuclear reactors powered power plants are under construction most of which are located at developing nations. Industry needs uninterrupted power supply round the clock. The power supply from nuclear power plants is ideal for such needs. Apart from capital intensity, the major hinderance in nuclear power expansion in developing nations is the severe shortage of nuclear skilled human resources. The lack of nuclear experience, knowledge, educational infrastructures, and resources is another constraint for developing nuclear skilled human resources in all emerging countries. This paper reviews the current trend of nuclear power plant development in developing countries and nuclear skilled human resources development models required for safe and cost-effective nuclear power plant design, construction, operation, maintenance, repair, and fuel management. The paper also highlights the nuclear engineering education institutions in South Asia.

Keywords: Nuclear energy, power plant, fossil energy, nuclear skilled human resources, education model.

1. Introduction

The rapid industrialisation and socio-economic development in emerging and developing nations propel the energy needs for power generation. The power requirement is further intensified by the increase of global population approximately 100 million per year. At present, nearly 25% global population mainly in Asia and Africa has no access to grid connected power [1-3]. Moreover, digitisation, electromobility and sector-coupling increase power demand further [4]. According to the International Energy Agency [5], World Energy Council [6] and Exxon Mobil [7], the global power demand will increase over 2% each year till 2040. As of December 2019, the global power generation by energy types is 38% by coal, 23% by natural gas, 16% by hydro, 10% by nuclear, 5% by wind, 3% by oil, 2% by solar PV cell, and 3% by other renewables including biofuel, geothermal, waste, tidal, etc. as shown in Fig. 1. Of the global nuclear power share, 37% is generated in North America (USA: 32%, Canada: 4%, Mexico 1%), 25% in European Union, 10% in Commonwealth of Independent States (CIS – mainly Russia, Ukraine, and Armenia), 25% in Asia led by China, South Korea, Japan, India, Pakistan and Iran; less than 1% in Africa (South Africa) and approximately 2% by the rest of the world (Brazil, Argentina, etc.). The nuclear power generation ratio for 2019 is shown in Table 1.

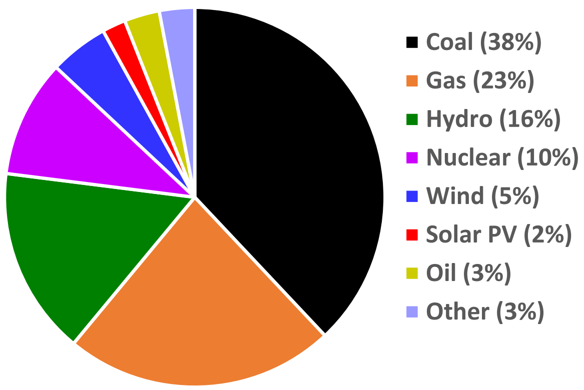

Fig. 1 Global Power Generation by Energy Type in 2019, adapted from [5]

Nuclear energy is considered a low carbon and low-emission energy source for power generation. The cost for power generation by nuclear energy is around 20-40% cheaper than natural gas, wind and solar (photovoltaic) energy. The power generation cost includes construction, operation, waste management and decommissioning [8-11]. The nuclear power remains a key clean-energy future for power generation unless and until the current fossil fuel power plants can be made less greenhouse gas polluters [1-2, 8-11]. As shown in Table 1, currently, 448

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nuclear reactors in 31 countries generate power over 391, 814 MW. It is the world's 2nd highest clean power after hydropower [1-2, 12].

Table 1 Nuclear power generating countries with nuclear power generation percentage in 2019, adapted from [7]

	Countries	% of Total Power
	Europe	
1	France	71
2	Ukraine	54
3	Slovakia	54
4	Hungary	49
5	Belgium	38
6	Bulgaria	38
7	Slovenia	37
8	Finland	35
9	Czech Republic	35
10	Sweden	34
11	Armenia	28
12	Switzerland	24
13	Spain	21
14	Russia	20
15	Romania	19
16	UK	16
17	Germany	13
18	Netherlands	3
	Asia	
1	South Korea	26
2	Chinese Taipei	15
3	Japan	8*
4	Pakistan	7
5	China (mainland)	5
6	India	3
7	Iran	2
	North America	
1	USA	20
2	Canada	15
3	Mexico	5
	South America	
1	Argentina	6
2	Brazil	3
	Africa	
1	South Africa	7

* Before Fukushima accident in 2011, its share was 30%.

2. Nuclear aspirant developing/ emerging countries

The volatile fossil fuel market, inadequate indigenous energy resources, environmental consciousness, rapid industrialisation, and economic development oblige emerging and developing countries to look for nuclear energy to generate power. The economic transformation in Asian nations is characterised by highest economic growth both in relative and absolute terms. It is predicted that nearly half of global Gross Domestic Product (GDP) would come from Asia by 2050. The share of Asia's total primary energy consumption is expected to increase to the half of global consumption (~ 48%). Europe and North America (including Mexico) would make up for about 30% of global total primary energy consumption from current 42%, Africa, including the middle East would account for 15% and South America - 7% [6]. As shown in Table 2, fifty-four (54) developing and emerging nations have expressed their intentions in acquiring nuclear technology for power generation. Furthermore, seven emerging nations are currently constructing nuclear power plants, some of which would be operational from 2021 (see Fig. 2).

The continent of Asia has started dominating in nuclear technology for power generation. Japan has 42 operational nuclear reactors and 2 under-construction reactors, China (excluding Chinese Taipei) has 39 operational and 17 under-construction reactors, South Korea has 24 operational and 2 under-construction reactors, and Chinese Taipei (Taiwan) has 6 operational and 2 under-construction reactors. In South Asia, India has 21 operational reactors in its 7 nuclear power plants in Maharashtra, Gujarat, Tamil Nadu, Rajasthan, Karnataka and Uttar Pradesh. Furthermore, there are 7 under-construction nuclear reactors. Pakistan has 5 operational reactors in two nuclear power plants located in Sindh and Punjab along with two more reactors under construction. Turkey and United Arab Emirates each has four under construction reactors while Bangladesh has two under construction reactors. Africa's second country (after South Africa), Egypt is expected to begin construction its first two reactors from the second half of 2021 at El Dabaa near Alexandria on the Mediterranean coast. Twelve more nations from Asia (Vietnam, Indonesia, Thailand, Philippines, Saudi Arabia, Uzbekistan and Jordan), Africa (Kenya and Nigeria) and South America (Bolivia) are in the final stage of planning to have their first nuclear reactors for power generation [1-2].

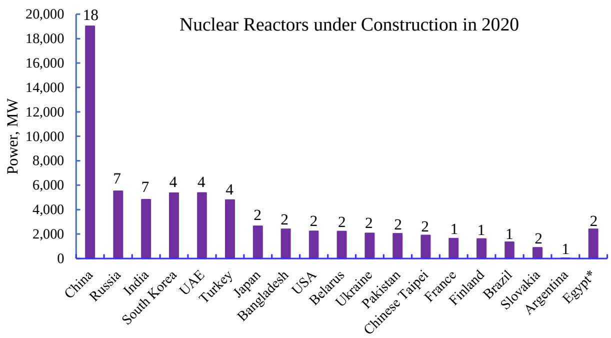

Fig. 2 Nuclear power reactors under constructions till November 2020, adapted from [1-2, 8-12]

Apart from China, Japan, South Korea, India and Pakistan, all emerging nations including Bangladesh have no prior nuclear experience. Nuclear power plants are extremely capital intensive and require highly skilled, committed, and disciplined human resources. Skilled human resources are paramount for planning, designing, constructing, and operating of a nuclear power plant. The inexperienced new-comer emerging nations rely almost entirely on nuclear reactor suppliers/ manufacturers for designing, constructing, testing and commissioning. Such heavy dependency can increase the capital and operating costs as well as compromise of compliance issues for national and international standards related to plant's warranty and safety [1-2].

Table 2 Nations considering nuclear power, adapted from [1-2]

	Europe		*Asia*
1	Italy	1	Saudi Arabia
2	Albania	2	Qatar
3	Serbia	3	Kuwait
4	Croatia	4	Jordan
5	Portugal	5	Azerbaijan
6	Norway	6	Georgia
7	Poland	7	Kazakhstan
8	Estonia	10	Mongolia
9	Latvia	11	Uzbekistan
10	Lithuania	12	Sri Lanka
11	Ireland	13	Indonesia
		14	Philippines
		15	Vietnam
		16	Thailand
		17	Malaysia
		18	Singapore
		19	Laos
		20	Cambodia
		21	Myanmar (Burma)
	Africa		*South America*
1	Tunisia	1	Chile
2	Algeria	2	Bolivia
4	Morocco	3	Peru
5	Sudan	4	Cuba
6	Libya	5	Ecuador
7	Nigeria	6	Venezuela
8	Kenya	7	Paraguay
9	Uganda		
10	Ghana		
11	Tanzania		
12	Zambia		
13	Namibia		
14	Senegal		
15	Rwanda		

3. Developing skilled human resources for nuclear power plant in emerging nations

The new construction boom of nuclear power plants in Asia, a return to new construction in Europe and North America, the desire to have nuclear power plants in many other emerging and developing nations in all continents, plant life extensions of existing nuclear power plants, and the retirement of experienced nuclear personnel from second generation power plants (since 1970s) have created an acute shortage in the global pool of nuclear skilled human resources. Every nuclear nation (existing or newcomer) needs to address these issues through long-term sustainable nuclear skilled human resources development roadmap [1-2, 13-15]. There is no hard and fast rule for the exact number of personnel required for a nuclear power plant which largely depends on nuclear experience of the country, level of science and technology base, exposure to nuclear industry, productivity, work ethics, commitment and proactive learning attitudes of the workforce. However, the personnel number should be at least three to four times more for a newly entrant developing country than a nuclear experienced developed country. Based on personnel required in nuclear power plants in European Union, Simonovska & Von Estorff [15]) sub grouped into three categories or personnel: a) nuclear (~16%), nuclearised (74%) and nuclear aware (10%) as shown in Fig. 3.

Nuclear personnel are core experts (nuclear scientists and nuclear engineers who received formal education in nuclear subjects such as nuclear engineering, radiochemistry, radiation protection, etc. Their expertise and knowledge are required to undertake nuclear projects successfully and efficiently in a nuclear organisation. Generally, these nuclear personnel (nuclear engineers, nuclear physicists, nuclear chemists, etc.) should be around 16% of the total workforce and have formal tertiary nuclear education (bachelor, master, PhD degrees).

Nuclearised personnel are people with formal education and training in a relevant (non-nuclear) area such mechanical engineering, electrical engineering, civil engineering, and other inter disciplinary engineering but who need to acquire knowledge of the nuclear environment in which they have to apply their engineering competencies. They are engineers (B.Eng./B.Sc.), technicians or diploma engineers and other science graduates. The typical ratio of this category of personnel in European nuclear industry is 35%: 38%: 27% respectively (see Fig. 3).

Nuclear-aware personnel are generally finance/accounting, general service givers, and other support staff. They need to have nuclear awareness to work in the industry. Their number should not exceed 10% of the total workforce.

To estimate personnel number for all three categories required for a nuclear power plant with a range of power generation capacity in nuclear developed and new-comer emerging countries, two equations have been developed. These equations are for an indicative number not for exact numbers. The exact number will depend on individual country's situation.

Personnel Number (PN) = *902.73* x **ln** ***(Plant Capacity in MW)*** - ***5097.6*** (1) for a nuclear developed nation.

Personnel Number (PN) = *1136.9* x **ln** ***(Plant Capacity in MW)*** – ***6410.7*** (2) for a new-comer developing country.

Where,

A - Nuclear (16%), B – Nuclearised Technicians (74% x 38%), Nuclearised Engineers (74% x 35%), Nuclearised Other Graduates (75% x 27%) and E – Nuclear-Aware (10%).

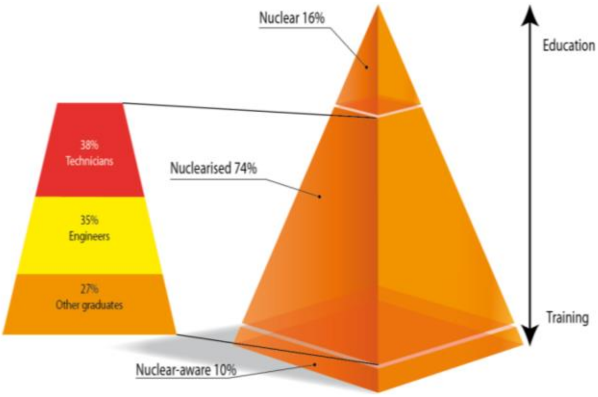

Fig. 3 Nuclear Skills type pyramid and number required for a nuclear matured developed country as a function of nuclear reactor size, adapted from [14-15].

Regardless of developed or developing nations, human resources recruitment and training process must begin 3 to 5 years prior to the start of nuclear power plant construction so that all personnel especially nuclear and nuclearized staff can be familiar and involved in the design, construction, testing and operation phases [16-18].

There are two nuclear human resources development models: one was formulated by the International Atomic Energy Agency (IAEA) and other was developed by Russia's State Atomic Energy Corporation 'Rosatom'. The IAEA model is shown in Fig. 4 and the Russian model is in Fig. 5. These models can be adapted for the development of nuclear human resources in a new entrant developing country. Both models require a lead time nearly 10 years. The IAEA and Rosatom models indicate that the human resources-development phases should include long term human resource development roadmap, workforce (nuclear, nuclearized and nuclear aware) recruitment and management plan with increasing exposure on nuclear power plant design, operation, maintenance, repair and emergency situation management [1-2]. The Rosatom human resources development model is very comprehensive. It emphasises the engagement of local nuclear engineering/nuclear science education institutions (ranging from high schools to universities) as well as reactor providing country's nuclear facilities and education institutions. The IAEA model clearly states that a country with no experience on nuclear technology requires a minimum of 15 years in 4 major phases as shown in Fig. 4 from the initial decision on acquiring nuclear technology to full-fledged operation of a nuclear power plant.

As per Rosatom skills development model, the nuclear education and training should start from the professional orientation-school followed by specialized high school/ college/ technikums/ polytechnics/ technical colleges, higher professional nuclear education institutions/universities. The continuous professional development (CPD) including theoretical training and on-the job-training in three major categories: i) category A (chief engineer), ii) category B (repair and modernisation head), and iii) category C (engineers, inspectors, supervisors, etc.) must be incorporated in the nuclear skilled human resources development model. The Rosatom roadmap also includes a) Competence Assessment Centres for different categories of personnel, b) Support Services for human resources development activities within the nuclear power plant company, c) Knowledge Management System customised to the requirements and legislation of the country (Fig. 5).

In South Asia, India and Pakistan have nuclear power plants over three decades. Until recently, nuclear human resources development in India was undertaken in-house by the Department of Atomic Energy (DAE), Nuclear Power Company India Ltd (NPCIL) and Homi Bhabha National Institute. Public and private education institutions had little or no role in nuclear human resources development. However, since 2010, education institutions (public and private) are permitted to offer nuclear education in graduate and postgraduate levels. At present twenty or more (mainly) public education institutions offer Bachelor, Master and PhD programs in nuclear engineering as shown in Table 3. Pakistan's nuclear education is still managed in-house. Nevertheless, three institutions (two in Karachi and one in Islamabad) offers postgraduate nuclear engineering education. In the new-comer country Bangladesh, four higher education institutions offer nuclear engineering and/ or nuclear science programs. The Military Institute of Science and Technology (MIST) is the only institution that offers Bachelor, Master and PhD programs in nuclear engineering in Bangladesh (Table 3).

At present, Bangladesh is constructing a lone nuclear power plant with two reactors each with 1,200 MW capacity at Rooppur in Pabna, a central western district of Bangladesh. The Rooppur Nuclear Power Plant (RNPP) is Bangladesh's largest infrastructure worth over 13 billion US dollars. The power plant is being built with the technical and financial assistance of Russia and it is dream project for Bangladesh government led by Sheikh Hasina (daughter of the country's founding Father, Bangabandhu Sheikh Mujibur Rahman) and Bangladesh populace. Both reactors are expected to be fully operational by 2024. Some milestones of RNPP construction activities are shown in Fig. 6.

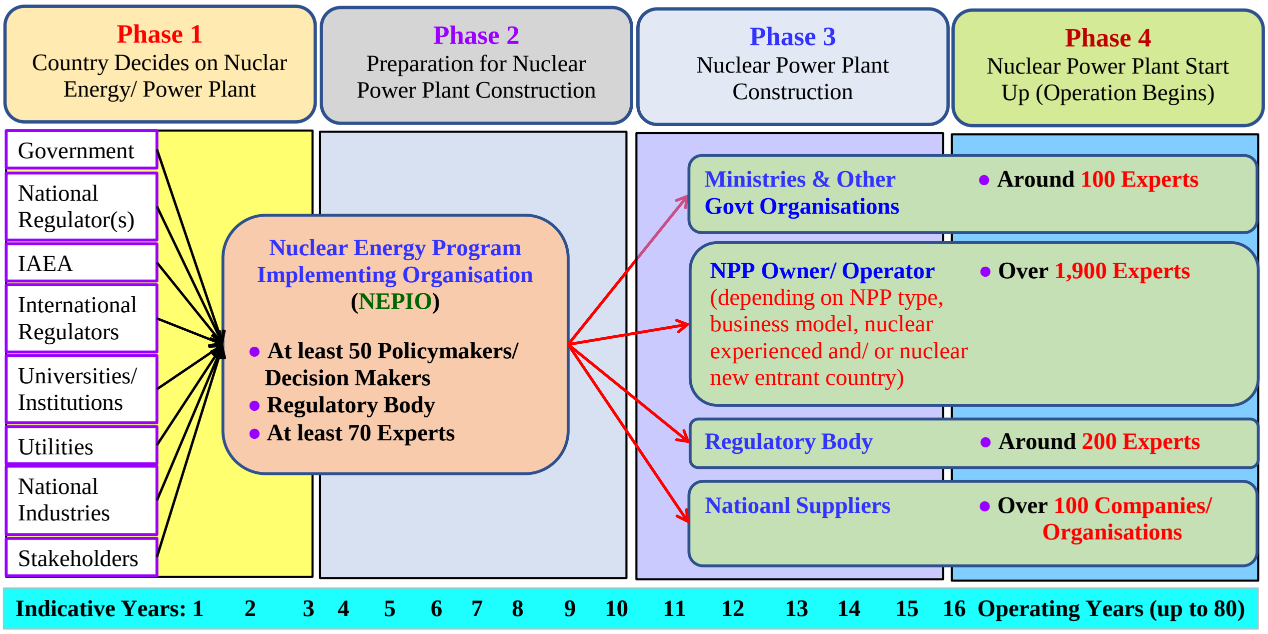

Fig. 4 IAEA recommended human resources development model, adapted from [1-2, 16-17].

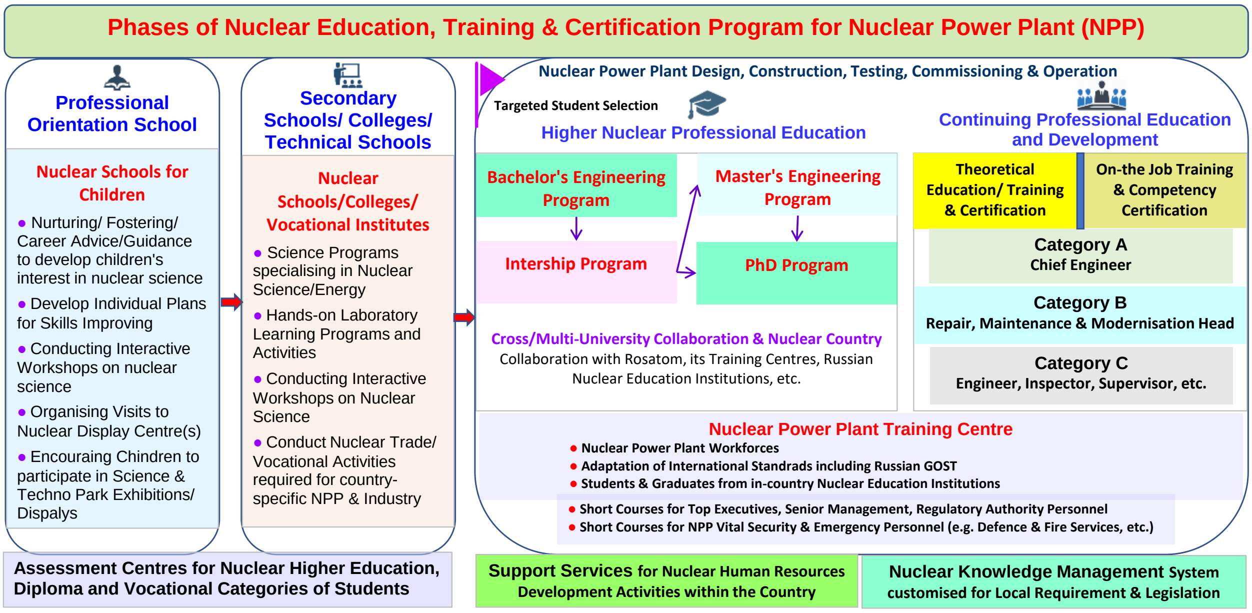

Fig. 5 Russian nuclear technical manpower development model, adapted from [1-2, 18]

a) Rooppur NPPsite, Bangladesh b) PM Sheikh Hasina poured first concrete with Rosatom Director c) Rooppur Nuclear City

d) Rooppur NPP construction e) Rooppur Unit 2 core catcher f) Core catcher installation g) Containment construction

Fig. 6 Rooppur nuclear power plant in Bangladesh, adapted from [1-2, 18]

Table 3 Institutions offering Bachelor, Masters and PhD Programs in Nuclear Engineering, adapted from [1-2]

	India	Courses
1	IIT Kanpur, Uttar Pradesh	M.Tech, PhD
2	IIT Bombay, Maharashtra	M.Tech
3	IIT Madras, Tamil Nadu	M.Tech
4	Bhabha Atomic Research Centre (Mumbai), Maharashtra	PhD
5	Pandit Deendayal Petroleum University (Gandhinagar), Gujarat	M.Tech
6	Homi Bhabha National Institute (Mumbai), Maharashtra	M.Tech
7	GH Raisoni College of Engineering (Nagpur), Maharashtra	M.Tech
8	School of Nuclear Energy (Gandhinagar), Gujarat	M.Tech
9	Amity Institute of Nuclear Science and Technology (Noida), Uttar Pradesh	B.Tech, M.Tech
10	Sastra University (Thanjavur), Tamil Nadu	M.Tech
11	Annai Mathammal Sheela Engineering College (Namakkal), Tamil Nadu	B.Tech
12	University of Petroleum and Energy Studies (Dehradun), Uttaranchal	M.Tech
13	Delhi Technological University (Formerly Delhi College of Engineering), New Delhi	M.Tech
14	Jawaharlal Nehru Technological University (JNTU) College of Engineering (Kakinada), Andhra Pradesh	M.Tech
15	Manipal Institute of Technology (Manipal-Udupi), Karnataka	M.Tech
16	Mody Institute of Technology and Science (Lakshmangarh), Rajasthan	M.Tech
17	SRM Institute of Science and Technology, Ramapuram Campus (Chennai), Tamil Nadu	B.Tech
18	University of Delhi, New Delhi	M.Tech
19	National Institute for Media Studies (Ahmedabad), Gujarat	B.Tech,, M.Tech, PhD
20	Jadavpur University (Kolkata), West Bengal	M.Tech
	Bangladesh	
1	Military Institute of Science and Technology, Dhaka	B.Sc., M.Sc., PhD
2	University of Dhaka	B.Sc., M.Sc.
3	Chittagong University of Engineering and Technology, Chittagong	B.Sc., M.Sc.
4	Bangladesh University of Engineering & Technology, Dhaka	M.Sc.
	Pakistan	
1	Pakistan Institute of Engineering & Applied Sciences, Islamabad	M.S., PhD
2	Karachi Institute of Power Engineering, Karachi	M.S.
3	Kanupp Institute of Nuclear Power Engineering, Karachi	M.S.

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4. Conclusions

One of the major challenges faced by emerging/ developing nations in nuclear energy utilisation for power generation is the acute shortage of nuclear skilled human resources. Therefore, nuclear ambitious countries must devise a national nuclear skilled human resources development roadmap incorporating existing vertically integrated national education institutions starting from high schools to universities.

Exchange of faculty members/ academic staff, sharing of equipment, infrastructure, other facilities and resources for teaching and research in nuclear engineering is highly recommended as no single institution can have required highly expensive resources.

Formation of consortium among education institutions and in-country nuclear power plant(s) will greatly help to produce required pool of nuclear skilled human resources.

Rosatom nuclear education model seems to be more suitable for developing countries as the model has evolved over long time and has proven track record.

The in-house tightly controlled human resources development program would not address the shortages of local and global nuclear skilled manpower. Hence, mainstream education institutions need to be proactive in sustainable nuclear skilled human resources preparation. This will ensure not only an uninterrupted delivery of nuclear knowledgeable and skilled human resources to meet the local and global needs but will also create a critical mass in nuclear knowledge creation, management, and dissemination.

7. Acknowledgement

The first, second and fourth authors express their sincere gratitude to Rosatom Technical Academy for conducting ‘Train the Trainers Course on Nuclear Power Plant for academics’ in Obninsk, Russia in 2018. The authors are also highly indebted to the management of Russia’s Novovoronezh Nuclear Power Plant for granting permission to visit the plant and its nuclear human resources development/training facilities.

8. References

[1] Alam F., Sarkar R., Paul A.R., Aldiab A., Nuclear Power Plants and Human Resources Development in South Asia. In: Bose M., Modi A. (eds) Proceedings of the 7th International Conference on Advances in Energy Research. Springer Proceedings in Energy. Springer, Singapore. https://doi.org/10.1007/978-981-15-5955-6_152, 2021.

[2] Alam, F., Sarkar, R. and Chowdhury, H., Nuclear power plants in emerging economies and human resource development: a review, Energy Procedia, vol.160, pp. 3-10, 2019.

[3] Smith, K. and Gieré, R., Why Some Nations Choose Nuclear Power, Kleinman Centre for Energy Policy, Newsletter, 23 June, 2017 https://kleinmanenergy.upenn.edu/policy-digests/why-some-nations-choose-nuclear-power (accessed on 10/11/2018).

[4] VGB Power Tech, Electricity Generation: Facts and Figures, 2019/2020, https://www.vgb.org/en/data_powergeneration.html?dfid=98054 (accessed on 10/11/2020)

[5] International Energy Agency (IEA) Electricity Information: Overview, July 2020, https://www.iea.org/reports/electricity-information-overview (accessed on 30/10/2020)

[6] World Energy Scenarios Composing energy futures to 2050, World Energy Council, Switzerland, 2013, https://www.worldenergy.org/assets/downloads/World-Energy-Scenarios_Composing-energy-futures-to-2050_Executive-summary.pdf (accessed on 12/11/2020)

[7] ExxonMobil 2019 Outlook for Energy: a Perspective to 2040, https://corporate.exxonmobil.com/-/media/Global/Files/outlook-for-energy/2019-Outlook-for-Energy_v4.pdf (accessed on 10/11/2020)

[8] World Nuclear Association 2020, https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx, (accessed on 01/11/2020)

[9] International Energy Agency (IEA) & Nuclear Energy Agency (NEA) Report on Projected Costs of Generating Electricity 2015, OECD, Paris, France, https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf (accessed on 01/03/2018).

[10] Masanet, E., Chang, Y., Gopal,A.R., Larsen, P., Morrow,W.R., Sathre,R., Shehabi,A. and Zhai, P., Life-cycle assessment of electric power systems, Annual Review of Environment and Resources, vol. 38, pp.107-136, 2013.

[11] IAEA 2016 Energy, electricity and nuclear power estimates for the period up to 2050. http://www-pub.iaea.org/MTCD/Publications/PDF/RDS-1-36Web-28008110.pdf (accessed on 01/10/2018).

[12] Nuclear Power Reactors in the World, IAEA Reference Data Series No. 2, 2018

[13] IAEA 2004 Report, The Nuclear Power Industry's Ageing Workforce: Transfer of Knowledge to the Next Generation, IAEA-TECDOC-1399, Vienna, https://www-pub.iaea.org/MTCD/Publications/PDF/te_1399_web.pdf (accessed on 20/10/2020).

[14] Roelofs, F., Estorff, U. Von., JRC Scientific and Policy Reports on Top-down workforce demand extrapolation from nuclear energy scenarios, European Commission, EUR 26008 EN, ISBN 978-79-30656-3, pp. 1-40, 2013.

[15] Simonovska, V., Estorff, U. Von, Putting into perspective the supply of and demand for nuclear experts by 2020 within the EU-27 Nuclear Energy Sector, Report EUR 25291, Netherlands, 2012.

[16] International Atomic Energy Agency, IAEA Nuclear Energy Series (NG-T-3.10): Workforce Planning for New Nuclear Power Program (IAEA), Vienna, 2011.

[17] International Atomic Energy Agency, IAEA Nuclear Energy Series (NG-G-2.1): Managing Human Resources in the Field of Nuclear Energy (IAEA), Vienna, 2009.

[18] The State Atomic Energy Corporation (Rosatom), Moscow, Russia, https://www.rosatom.ru/en/ (accessed 11/06/2018).

ICMIEE20-KN07

Acoustic Emission Technique, a Nondestructive Monitoring Tool for Damage Detection and Evaluation

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ABSTRACT
Acoustic emission (AE) signals that are generated due to the sudden rearrangements of stresses inside a material as elastic waves, are widely used in non-destructive testing (NDT) of material cracking especially in health monitoring of structures for damage detection as well as in plant maintenance etc. When a body is subjected to an external stimulus (in the form of changing pressure, load, or temperature), any micro fracture inside the body releases energy in the form of AE wave which is received by AE sensor, later on, is converted to electrical signals termed as AE signals for internal inspection. This evaluation technique is termed as acoustic emission technique. In early stage, major importance was given on studying the AE characteristics during the deformation and fracture on various materials (by J. Kaiser in Germany in 1950, by B. H. Schofield in the U. S. in 1954). However, as the time passed, lots of researches have been conducted in different fields about behavioral formulation, theoretical explanation as well as experimental validation of this technique in AE signal generation, propagation and inspection with various kinds of deformations as an important health monitoring tool for NDT. In the present topic, features outlook of AE based nondestructive monitoring technique perspective to the damage detection and evaluation are planned to be elaborated. Basic theories, experiments related to the material cracking behavior are included to the presentation. Source localization of internal damage that has become an important characteristic feature in AE technique based NDT is also planned to be elaborated to this presentation. Furthermore, AE technique perspective to the advanced applications are also summarized in the present topic. Several practical research results are planned to discuss in the proposed presentation as well.

Keywords: Acoustic emission, non-destructive testing, structural health monitoring.

ICMIEE20-KN08

Industry 4.0, Digital Twin and Global Competition – Challenges and Opportunities

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ABSTRACT
According to the World Economic Forum, 65% of children entering primary school today will ultimately end up working in completely new job types that currently do not exist. Industry 4.0 transformation is shaping our talent pipeline in the manufacturing industry. Disruptive technologies are forcing the development of new business models. Uber Technologies has nearly eliminated long standing taxi industries. Nowadays the biggest question is who will win the game of smart industrialized revolutions? Lack of skilled qualified workforce with this smart integration is forcing academic community to embrace new smart curriculum. This talk will showcase the challenges and opportunities of disruptive technologies in industrial sectors. Industrial engineering tools and techniques can prepare the next generation workforce for the upcoming challenges. Digital twin and MSV (Modeling, Simulation and Visualization) from the Automation Alley Industry 4.0 will presented. Readiness of engineering graduates on smart technologies and continuous improvement around the global are various. Focues should be given to reduce the gaps globally. It will add global competitiveness. Automotive supply chain and logistics optimization will be presentation with smart integration.

Keywords: Industry 4.0, Smart Manufacturing, Digital Twin, Supply Chain and Logistics

ICMIEE20-KN09

Development of Smart Materials for Invasive Medical Applications Using Shape Memory Polymers

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ABSTRACT

Shape memory polymers (SMPs) represent an intelligent polymeric material which can fix deformed temporary shape and recover their permanent shapes upon an external stimulus such that temperature, light, electricity, water, pH, magnetism and specific ions. This property is called shape memory effect (SME). The SME has underpinned its usefulness of SMPs in delicate minimally invasive surgeries (MIS's) such as vascular stents, clot removals etc. The invasive biodegradable SMP devices can avoid second surgery and have a great potential over any conventional metallic biomedical device. The ability to change triggering temperature to use in a broader range of temperatures while keeping SME is another superior capability of SMPs. Additionally, SMPs have shown a good prospective due to their special characteristics such as biocompatibility, biodegradability, low rejection by host and low density. However, intrinsic low stiffness, strength and recovery stress possess a significant limitation in the applications of SMPs. In-depth literature survey has revealed that many existing concepts were terminated without further continuation. This may be mainly due to strict, lengthier Vitro and Vivo certification process. Therefore, to date, a limited number of invasive products have been realized and commercially available. This paper provides a brief overview of current SMP based invasive medical applications, status and limitations. This review will be more beneficial to identify current research gaps, for those who are emerging into SMP based invasive biomedical applications.

Keywords: Shape Memory Polymers, Biomedical, Invasive Applications, Stents.

1. Introduction

Shape-memory polymers (SMPs) are a class of mechanically functional "smart" materials that have gained substantial attention in the development of biomedical applications. Since 1932 researchers have comprehensively studied shape memory effect (SME) of shape memory alloys (SMAs) for its potential use in medical field [1]. The same phenomenon was later observed in polymers with both thermal and athermal stimuli responsiveness [2]. The recently synthesized SMPs inspired biomedical engineering due to properties of low systemic toxicity, lightweight, sterilizability, biocompatibility and natural biodegradability. In contrast to many alloys, SMPs are generally well recognized as a biocompatible material [1].

The rapid development in chemical engineering facilitated synthesization of improved biodegradable and biocompatible SMPs. SMPs have desirable features, such as large recovery ability, lightweight, superior processability and low cost have generated enthusiasm among the scientists. The tailored activation temperature offered greater flexibility to fabricate surgical implants that can be designed to self-activate at body temperature without cell tissue damage. The large strain recovery allowed the device to be inserted through a small cut. The developed new materials were subjected to a strict biological certification through in Vitro and in Vivo models [3]. To date, minimal invasive cardiovascular stents are well researched in the field of SMPs. The more success of SMP minimal invasive techniques, sooner this will replace complicated traditional balloon stent deployment method. Apart from that clot removal devices, embolization techniques, drug delivery systems are already investigated, and some recent developments are discussed in this review.

2. Shape Memory Materials (SMMs)

Most commonly, memory of SMP materials are triggered by thermal activation, either directly or indirectly [4, 5]. Among them, thermal and solvent stimuli are prominent in biomedical applications [6, 7]. Energy and molecular structure theories are utilized to explain shape memory mechanism of SMPs [8].

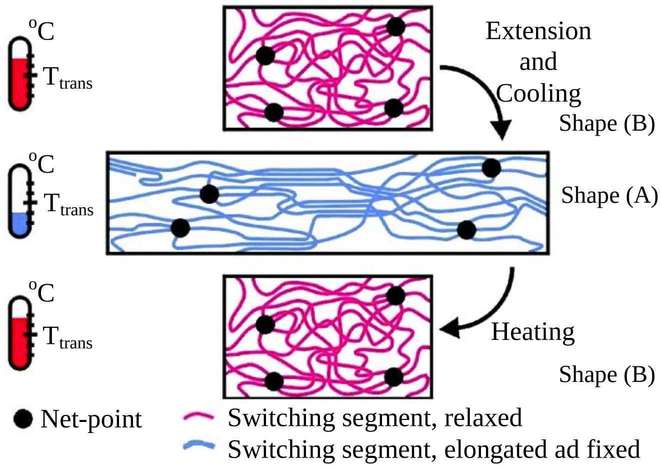

Fig.1 Molecular mechanism of the thermally induced SME [9].

The permanent shape has low entropy; hence it is more stable. Above activation temperature, material deform and transform into higher energy state before trapping upon cooling. Again, beyond transition temperature (glass transition temperature (T_g), melting

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temperature (T_m), and isotropic temperature (T_i)) polymer network can release energy and become a stable, permanent shape. T_g is used to describe chemically cross-linked thermoset materials and physically cross-linked thermoplastic polymers. T_m can be used to define semi-crystalline polymer networks and chemically cross-linked rubbers. In the molecular point of view, the SMP network is incorporated with net-points and switchers (Fig. 1) [10]. The net points associated with chain segments which govern the permanent shape and switchers are more sensitive to external triggering, which allows material deformation temporally [10]. The temporary shape fixation is obtained through solidification of the switching domain, which can be achieved through chemical or physical changes.

3. Thermomechanical Behavior of SMP

Apart from biocompatibility and degradability, biomaterials should have flexibility and rigidity depending upon the applications. These two parameters are defined the elastic modulus of the material. The elastic modulus differs significantly above and below the transition temperature (T_{trans}). This elastic modulus difference is due to the restriction of micro-Brownian movements below T_{trans} [11]. Hence, to assure the product functionality and standardize shape memory properties, shape recovery (R_r) and shape fixity (R_f) properties are defined [12]. The most widely accepted SMP classification as follows (Fig. 2).

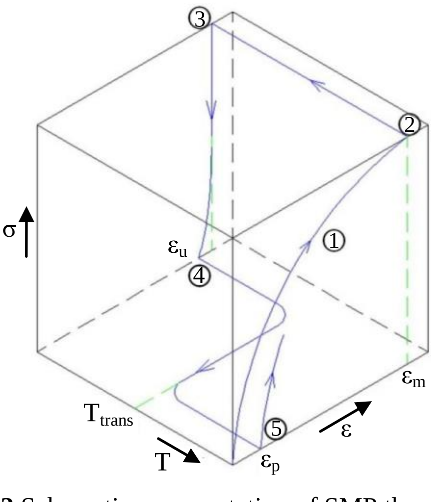

Fig.2 Schematic representation of SMP thermo-mechanical cycle [13].

① Deformation to the desired temporarily shape
② The desired temporarily shape is achieved
②−③ Decrease of the temperature below T_{trans}
③−④ Removal of the stress by removing the material out of the testing machine
②−④ Fixation of the temporary shape
④−⑤ Increase of the temperature above T_{trans}

Programming: The SMP is heated closer or above T_{trans} and can be formed into a specified shape by compression, extrusion or injection moulding [14].

Storage: SMP is cooled and held in its temporary shape. This occurs below the T_{trans} and constrains are released once cooling has finished.

Recovery: Upon reheating, SMP is activated and returns to its permanent shape.

During the thermomechanical cycle, elastic portion stores the energy and viscous portion dissipates energy [15]. To describe the phenomenon, storage elastic modulus (E”) and loss elastic modulus (E’) can be used. The ratio is defined as loss tangent modulus (Tan δ= E”/E’). To understand and obtain these parameters, usually, Dynamic Mechanical Analysis (DMA) tests are carried out.

4. Invasive SMP Applications

Compared to other fields of research, SMPs in the biomedical field have shown a large number of applications, especially in biomedical devices they are used for minimal invasive surgeries [16]. The first successful polyurethane-based biodegradable and biocompatible material was developed by Mitsubishi Heavy Industry (MHI) Japan [17]. MedShape, USA is one of the leading company among a few other industries which produce those products [2]. The MedShape holds a patent for SMP soft tissue anchor and the product is already approved by Food and Drug Administration (FDA). The soft tissue anchor is commercially available in different diameters and different lengths. Professor Lendlein is the pioneer in the SMP based bio-medical device development and has developed distinct nature of applications such as self-tighten sutures, ureteral stent.

4.1 SMP Stents

Poly-l-lactic acid (PLA, PLLA), poly glycolic acid (PGLA), Chitosan, poly(Ɛ-caprolactone) (PCL) and Polyurethane based stents can be seen in the SMP stent field. Among those, PCL based SMP stents are more popular.

Fig.3 Igaki-Tamai self-expandable PLLA stent [18].

Tamai et al. [18] made poly-l-lactic acid (PLLA) based helical shape self-expandable springy coronary stents, which had 0.17 mm strut thickness. The stent was deployed with a hot liquid balloon, and Vivo preliminary study showed that the stent took 0.2 seconds in 70^{o}C temperature and 20 minutes in 37^{o}C (Fig. 3). The higher activation temperature can damage human body cells. However, the research team successfully installed 25 stents in selected patients. Tamai coronary stent was believed to be the first successful replacement for the conventional metallic stent. As a further continuation and improvement Venkatraman et al. [19] developed PLLA and PGLA bi-layer self-responsive SMP stent (Fig. 4).

Fig.4 Venkatraman bi-layer stent [19].

PLLA/PLGA:0.08/0.07 thickness ratios showed minimum 36% recoil percentage within 8 minutes at 37^{o}C water. The stent took 15 days to recover in 37^{o}C water. Vratika et al. [20] fabricated a self-expandable stent with PLGA and PLA biomaterials. The polymer composition was mixed with 3:2 ratio, and the stent was 0.25 mm thick. The Vivo experiment was conducted in goat vessel. Further, Vratika et al. showed that the stent could carry maximum of 500g drugs without sacrificing mechanical strength.

Lauto et al. [21] helically wound 0.055±0.005 mm thick chitosan (4% w/v) stent tested with Wistar rats, and no granuloma was observed after two weeks of deployment. The stent self-expanded over 50% of its initial diameter within 3 minutes, and the expansion process was irreversible. As a further continuation, Chen et al. [22] developed an epoxy eluted SMP stent. In 37^{o}C aqua environment, the stent recovered its permanent shape within 150 seconds (Fig. 5). Compared to Tamai et al. and Venkatraman et al. stents models, Chen et al. SMP stent model showed a fast recovery.

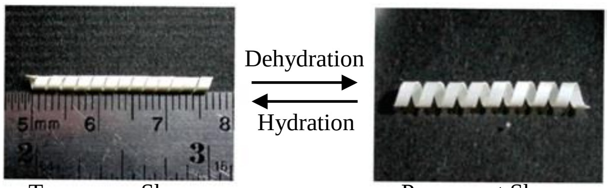

Fig.5 Chen PLLA, PLGA based stent [22].

Fabricated chitosan SMP stent was implanted in the rabbit's abdominal aorta, and clinical examination revealed that no thrombus formed during the delaminated period. Further continuation to this, Chen et al. [23] developed chitosan-based epoxy cross-linked Sirolimus-eluting hydrophobic heparin-coated biodegradable SMP stent. The Vivo results revealed that using a heparin layer can control the drug release rate of the stent. However, after that, none of the researchers were interested in chitosan-based stents.

SMP researches frequently used polyurethane based SMP materials due to their unique properties such as biocompatibility, higher strain and more comfortable mass scale manufacturing. Wache et al. [24] proposed a 30 mm long stent catheter which can load 35% of drugs maximally. However, the stent activation temperature was around 80-120^{o}C, which is not suitable for biomedical applications. Another polyurethane SMP stent was fabricated by Geraldine et al. [25], which can be triggered using laser energy. The thermoplastic polyurethane (TPU) pallets chemicals were obtained from HMI Japan. The Differential Scanning Calorimetry (DSC) results revealed that the stent can deploy around 40^{o}C, and most importantly, the activation temperature (T_g) can be varied from 30^{o}C to 86^{o}C by varying the chemical composition. Moreover, in zero flow condition, 8.6 W laser power was consumed during the activation and took 6.3 minutes. The time taken for activation was too long, and in real physiological condition (flow at 180 ml/min) it may take more. However, using fibre-optics, the required laser power can be concentrated into the required location rather than heating the whole stent. Additionally, Duarah et al. [26] have made three different stents with hyperbranched polyurethane (HPU) incorporated with biocompatible (CD-Ag) Nano-hybrid in different weight ratios. The stents were operated at tiny (37±1)^{o}C temperature range with higher fixity and recovery ratios. Further, Zou et al. [27] developed electromagnetically activated SMP composing Fe_3O_4 with polyurethane. The stent activated at 42^{o}C, and up to 20% nanoparticles did not change the mechanical properties of the stent. In addition to that Fe_3O_4 incorporated stent materials and stent models were proposed by Yakacki et al. and Gu et al. [11, 28].

Poly(Ɛ-caprolactone) (PCL) is the most tested material in SMP biomedical stents. The PCL activation temperature (T_m) is around 60^{o}C and relatively higher for human invasive applications. To reduce the activation temperature, different co-polymers were introduced. Bellin et al. [29] introduced triple SME PCL based sent. The stent can be inserted into to human body as a compressed shape, and other two temporarily shapes can be used to facilitate and removal. Yu et al. [30] synthesized PLA with PCL with 10/90 weight ratios and named as poly(Ɛ-caprolactone-co-DL-lactide)/PCLA. The mechanical properties of the material were similar to Ni-Ti alloy. The fabricated stent triggered at 37^{o}C, and the dimensions of the stent were 13 mm length and 30 mm outer diameter, respectively. Yu et al. verified their SMP stent by implanting it in a dog's esophagus, and a minimally invasive technique was used (Fig. 6). Yang et al. proposed a faster self-expandable sent, which has activation temperature around 39-40^{o}C. The stent took 25 seconds to trigger in the body fluid environment. As a continuation, Yang et al. [31] manufactured PCL and polyethylene glycol (PEG) cross-linked drug-eluting biodegradable stent. The stent activated within 10 seconds in 40^{o}C and showed fixity and recovery greater than 99% and 90% respectively. Moreover, the stent showed an excellent drug-eluting capability without showing a structural deformation.

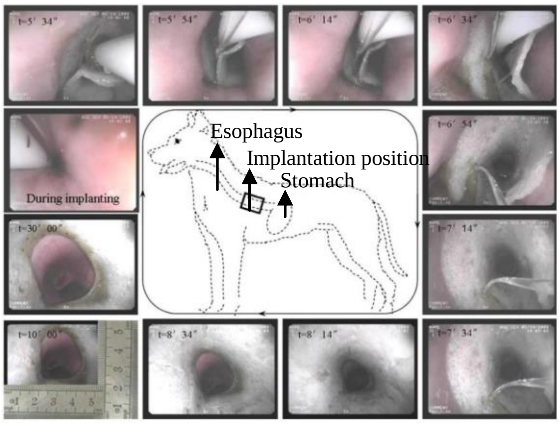

Fig.6 PCLA stent in dog's esophagus [30].

Boire et al. [32] developed a thermally activated SMP from poly (α-allyl carboxylate-ε-caprolactone) (ACPCL) and PCL. The triggering temperature of the material was around 37°C. To prove the functionally, the stent was implanted in the femoral artery near to thigh muscle in A/J mice. However, Boire et al. requested long term Vivo study to prove the stent capability before using in human. Another PCL based SMP material was developed using melt blending method by Zheng et al. [33]. The optimized composition of the material mainly consisted of poly (propylene carbonate) (PPC) with 25% PCL and was named as PL-25. Initially, the stent was eluting the drug at a higher rate and afterwards showed a linear proportion. Within two months, the stent eluted nearly 60% drug content compared to the total mass of the stent.

Ajili et al. [34] made new stent material after melt blending PCL and polyurethane (PU). The optimum properties were obtained at PU/PCL:70/30 weight ratio, and the activation temperature was around 37°C. Most importantly, Ajili et al. proved the biocompatibility of new stent and stent supported cell adhesion and proliferation. As an advancement Ansari's group further developed PU and PCL integrated SMP material. However, they used a blend mixing method which showed higher storage modulus and loss modulus compared to Ajili et al.'s stent material [16, 34]. The mixing ratios were the same as Ajili mentioned above. Thermomechanical tests revealed that the relaxation was high due to diameter/thickness ratios. Therefore Ansari et al. concluded that geometry is significantly affected on recovery response of the stent.

4.2 SMP Embolization Techniques

Embolization is a medical technique currently used by most surgeons to block the blood flow to a particular area inside the body. It helps to prevent massive internal bleedings, control the blood flow, block the blood flow to tumors and eliminate abnormal connection to veins. SMP researchers developed embolization techniques with the help of SME. Redriguez et al. [10] tested filling type embolization and used polyurethane-based material as a filler. Redriguez intended to replace coil type traditional embolization technique with filling type material. In addition to that biocompatibility of the material was also verified during swine Vivo model. Later, Redriguez et al. [35] tested foam type SMPs for vascular applications (Fig. 7). Landsman et al. [36] further studied the foam type embolization materials and mainly focused on the activation temperature, the time required to deploy it into the correct place without activation. The efficiency of the device was verified by performing blood flow studies. Further, the study of swelling capacity is much essential to avoid tissue damage during the process. The pilot study revealed that 37°C water did not exceed 0.6 N, and with this load, cell damage is unlikely to happen. Nathan et al. [37] further stated that without damaging cells, foams can be used to block the blood vessels. Therefore, authors believe that SMP foams are potential candidates for embolization devices shortly.

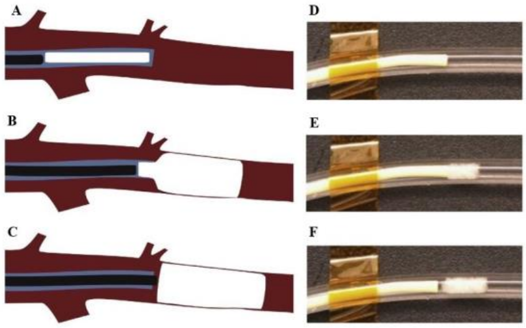

Fig.7 Endovascular deployment of the SMP [35].

(A)-The device is pushed near the catheter tip by the guidewire, (B)-The guidewire pushes the self-actuating device out of the catheter, (C)-Deployed device fills the vessel lumen, (D–F)-In Vitro demonstration of developed occlusion device in 37°C (Body temperature).

4.3 SMP Clot Removing Devices

The blood clots can obstruct the arterial supply and cause ischemic stroke, resulting in permanent disability or death. Conventionally the blood clots can be dissolved with drug treatments; however, the uncertainty of the process is high, and takes a long time.

Gobin et al. [38] developed an SMP corkscrew-like catheter to remove the clots inside blood vessels. The radiologist can insert straighten thermoplastic SMP wire into a micro-catheter and feed the catheter until it reaches the clot. After that, pushing the SMP wire out and due to the triggering, the shape is changed into the corkscrew shape. The temporary helical shape can trap the blood clot and then the catheter is pulled out. This method may require multiple catheters. In certain occasions, the SMP wire could not capture the whole clot due to early activation. Hartman et al. [39] proposed a thermosetting micro-actuator to address this issue. However, the success of the procedure is highly dependent on the skill and experience of the surgeon.

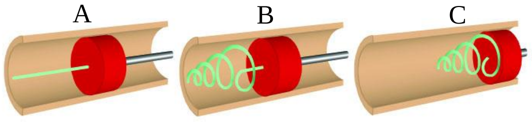

Fig.8 Laser-activated SMP micro-actuator [40].

(A)-The temporary straight rod form, (B)-The permanent corkscrew from by laser heating, (C)-The deployed micro-actuator is retracted to capture the thrombus

Small et al. [40] developed a novel bool clot removal method from thermoplastic polyurethane from MHI Japan. The SMP micro-actuator tip is made of optical fibre which can be activated 810 nm laser light (Fig. 8). To obtain the primary corkscrew shape, specially designed mandrel was used. The corkscrew SMP specimen was heated before straightened manually into a temporary rod shape. The device was tested under 37^{o}C static water and actuated within 3 seconds in 4.89W laser power. During the Vitro test, the device successfully captured the artificial blood clot in the water-filled bifurcated vessel model underflow.

4.4 Other SMP Invasive Applications

The SMP capsule is designed to control the obesity problem in the society [41]. The foam capsule is placed inside the stomach using the endoscopic tool (Fig. 9).

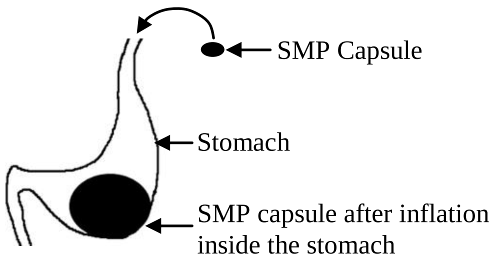

Fig.9 SMP gastric implantation [41].

The same endoscopic tool is used to stimulate SMP capsule. After implantation the person feels less hungry due to the less space inside the stomach. The same endoscopic tool can be used to remove the capsule after deflation.

Lendeline et al. [42] developed a ureteral stent from PCGDMA based biocompatible SMP. The stent can be anchored inside the ureter, and upon stimulus, the ureter can be open. This type of device is more useful for those who are having abdominal tumors. However, the fewer number of researches were seen in these areas, and there is more room to improve the reliability of SMP gastric capsule and ureteral stent.

5. Critical Factors on Invasive SMP Biomedical Applications

Recently, many different types of SMP materials are synthesized with different techniques such as dip coating, solvent casting injection moulding. Biocompatibility and degradability are already verified among limited number of materials. Above literature clearly shows that the most SMP materials are synthesized to develop stents. However, implanting a polymer device inside a human body is quite a challenging process. Moreover, few researchers have assessed the deployed device performance under real body fluid environment through Vivo models. The long-term functional analysis is hardly observed. Many researchers' proposed concepts that are terminated without further continuation due to the strict certification process. On the other hand, material functional ability, such as activation temperature, was proved with heated water. Mechanical properties of the synthesized materials were presented under normal environmental conditions. However, under complex body fluid condition, mechanical properties were hardly investigated. Therefore, many research areas still need to be improved. Due to abovementioned reasons, many successful outcomes are commercially not available to date. Table 1 shows strength and limitation of SMPs in invasive biomedical applications.

Table 1 SMP strength and limitation in invasive applications.

Strengths	Limitations
Good recovery strain	Low recovery force
Easy fabrication	Poor mechanical properties
Cost-effective	Poor electrical conductivity
Lightweight and non-toxic	Packaging and storage
Biocompatible	Transporting issues
Biodegradable	Fatigue susceptibility
Tunable thermal properties	Short life cycle

6. Requirement for SMP Non-Invasive Applications

SMP researchers showed immense interest in the aforementioned different types of invasive applications. On the other hand, few scientists were interested in non-invasive biomedical applications with SMP, and even to date they are in the preliminary stage. The present researchers were aiming to use SME effectively on non-invasive applications. For example, Manzoor et al. conducted a feasibility study on SMP pressure bandage with polyurethane SMP in 2012, and Zhao et al. presented an adaptive repair device in 2012 [41, 42]. Therefore, there will be many non-invasive type applications available very soon.

7. Summary

To date, material synthesization techniques and advanced manufacturing methods can overcome many unresolved issues in the SMP biomedical field. Therefore, authors believe that more systematic scientific research is needed in both invasive and non-invasive applications. Since both types of medical devices and equipment will help to overcome the potential complications and drawbacks in the current surgical procedures.

8. References

[1] M. D. Hager, S. Bode *et al.*, "Shape memory polymers: Past, present and future developments," *Progress in Polymer Science,* vol. 49-50, pp. 3-33, 2015, doi: 10.1016/j.progpolymsci.2015.04.002.

[2] S. Glock, L. P. Canal *et al.*, "Magneto-mechanical actuation of ferromagnetic shape memory alloy/epoxy composites," *Composites Science and Technology,* vol. 114, pp. 110-118, 2015, doi: 10.1016/j.compscitech.2015.04.009.

[3] D. Yang, W. Huang *et al.*, "Electromagnetic activation of a shape memory copolymer matrix incorporating ferromagnetic nanoparticles," *Polymer International,* vol. 61, no. 1, pp. 38-42, 2012, doi: 10.1002/pi.3188.

[4] J. Xu and J. Song, "High performance shape memory polymer networks based on rigid nanoparticle cores," *Proc Natl Acad Sci U S A,* vol. 107, no. 17, pp. 7652-7, Apr 27 2010, doi: 10.1073/pnas.0912481107.

[5] H. M. C. M. Herath, J. A. Epaarachchi *et al.*, "Structural performance and photothermal recovery of carbon fibre reinforced shape memory polymer," *Composites Science and Technology,* vol. 167, pp. 206-214, 2018, doi: 10.1016/j.compscitech.2018.07.042.

[6] Y. Kai, L. Yanjiu *et al.*, "Conductive Shape Memory Polymer Composite Incorporated with Hybrid Fillers: Electrical, Mechanical, and Shape Memory Properties," *Journal of Intelligent Material Systems and Structures,* vol. 22, no. 4, pp. 369-379, 2011, doi: 10.1177/1045389x11401452.

[7] H. Y. Jiang, S. Kelch *et al.*, "Polymers Move in Response to Light," *Advanced Materials,* vol. 18, no. 11, pp. 1471-1475, 2006, doi: 10.1002/adma.200502266.

[8] D. L. Safranski, K. E. Smith *et al.*, "Mechanical Requirements of Shape-Memory Polymers in Biomedical Devices," *Polymer Reviews,* vol. 53, no. 1, pp. 76-91, 2013, doi: 10.1080/15583724.2012.752385.

[9] M. Behl and A. Lendlein, "Shape-memory polymers," *Materials Today,* vol. 10, no. 4, pp. 20-28, 2007, doi: 10.1016/s1369-7021(07)70047-0.

[10] C. O. Correia and J. F. Mano, "Chitosan scaffolds with a shape memory effect induced by hydration," *J. Mater. Chem. B,* vol. 2, no. 21, pp. 3315-3323, 2014, doi: 10.1039/c4tb00226a.

[11] S.-Y. Gu, S.-P. Jin *et al.*, "Polylactide-based polyurethane shape memory nanocomposites (Fe3O4/PLAUs) with fast magnetic responsiveness," *Smart Materials and Structures,* vol. 25, no. 5, 2016, doi: 10.1088/0964-1726/25/5/055036.

[12] D. L. Safranski and J. C. Griffis, *Shape-Memory Polymer Device Design*. William Andrew, 2017.

[13] W. Rottiers, L. Van den Broeck *et al.*, "Shape Memory Materials and their applications," in *Korolev's readings: conference proceedings*, 2011: Samara State Aerospace University, pp. 250-251.

[14] M. Behl, M. Y. Razzaq *et al.*, "Multifunctional shape-memory polymers," *Adv Mater,* vol. 22, no. 31, pp. 3388-410, Aug 17 2010, doi: 10.1002/adma.200904447.

[15] B. Chasse, H. Xu *et al.*, "In-vitro biodegradation study of poly(ε-caprolactone) films using a 3D printed helical flow prototype to simulate the physiological conditions for cardiovascular implanted devices," *Biomedical Physics & Engineering Express,* vol. 5, no. 6, 2019, doi: 10.1088/2057-1976/ab4e2b.

[16] Y. Zheng, Y. Li *et al.*, "Biocompatible Shape Memory Blend for Self-Expandable Stents with Potential Biomedical Applications," *ACS Appl Mater Interfaces,* vol. 9, no. 16, pp. 13988-13998, Apr 26 2017, doi: 10.1021/acsami.7b04808.

[17] W. Sokolowski, A. Metcalfe *et al.*, "Medical applications of shape memory polymers," *Biomed Mater,* vol. 2, no. 1, pp. S23-7, Mar 2007, doi: 10.1088/1748-6041/2/1/S04.

[18] H. Tamai, K. Igaki *et al.*, "Initial and 6-month results of biodegradable poly-l-lactic acid coronary stents in humans," *Circulation,* vol. 102, no. 4, pp. 399-404, 2000.

[19] S. S. Venkatraman, L. P. Tan *et al.*, "Biodegradable stents with elastic memory," *Biomaterials,* vol. 27, no. 8, pp. 1573-8, Mar 2006, doi: 10.1016/j.biomaterials.2005.09.002.

[20] V. C. Sonawane, M. P. More *et al.*, "Fabrication and characterization of shape memory polymers based bioabsorbable biomedical drug eluting stent," *Artif Cells Nanomed Biotechnol,* vol. 45, no. 8, pp. 1740-1750, Dec 2017, doi: 10.1080/21691401.2017.1282867.

[21] A. Lauto, M. Ohebshalom *et al.*, "Self-expandable chitosan stent: design and preparation," *Biomaterials,* vol. 22, no. 13, pp. 1869-1874, 2001.

[22] M.-C. Chen, H.-W. Tsai *et al.*, "Rapidly Self-Expandable Polymeric Stents with a Shape-Memory Property," *Biomacromolecules,* vol. 8, no. 9, pp. 2774-2780, 2007/09/01 2007, doi: 10.1021/bm7004615.

[23] M. C. Chen, Y. Chang *et al.*, "The characteristics and in vivo suppression of neointimal formation with sirolimus-eluting polymeric stents," *Biomaterials,* vol. 30, no. 1, pp. 79-88, Jan 2009, doi: 10.1016/j.biomaterials.2008.09.006.

[24] H. Wache, D. Tartakowska *et al.*, "Development of a polymer stent with shape memory effect as a drug delivery system," *Journal of Materials Science: Materials in Medicine,* vol. 14, no. 2, pp. 109-112, 2003.
[25] G. M. Baer, W. t. Small *et al.*, "Fabrication and in vitro deployment of a laser-activated shape memory polymer vascular stent," *Biomed Eng Online*, vol. 6, p. 43, Nov 27 2007, doi: 10.1186/1475-925X-6-43.
[26] R. Duarah, Y. P. Singh *et al.*, "High performance bio-based hyperbranched polyurethane/carbon dot-silver nanocomposite: a rapid self-expandable stent," *Biofabrication*, vol. 8, no. 4, p. 045013, Oct 27 2016, doi: 10.1088/1758-5090/8/4/045013.
[27] H. Zou, C. Weder *et al.*, "Shape-Memory Polyurethane Nanocomposites with Single Layer or Bilayer Oleic Acid-Coated Fe3O4Nanoparticles," *Macromolecular Materials and Engineering,* vol. 300, no. 9, pp. 885-892, 2015, doi: 10.1002/mame.201500079.
[28] C. M. Yakacki, N. S. Satarkar *et al.*, "Shape-memory polymer networks with Fe3O4nanoparticles for remote activation," *Journal of Applied Polymer Science*, vol. 112, no. 5, pp. 3166-3176, 2009, doi: 10.1002/app.29845.
[29] I. Bellin, S. Kelch *et al.*, "Polymeric triple-shape materials," *Proceedings of the National Academy of Sciences,* vol. 103, no. 48, pp. 18043-18047, 2006, doi: 10.1073/pnas.0608586103.
[30] X. Yu, L. Wang *et al.*, "A shape memory stent of poly(epsilon-caprolactone-co-DL-lactide) copolymer for potential treatment of esophageal stenosis," *J Mater Sci Mater Med,* vol. 23, no. 2, pp. 581-9, Feb 2012, doi: 10.1007/s10856-011-4475-4.
[31] C. S. Yang, H. C. Wu *et al.*, "Thermo-induced shape-memory PEG-PCL copolymer as a dual-drug-eluting biodegradable stent," *ACS Appl Mater Interfaces,* vol. 5, no. 21, pp. 10985-94, Nov 13 2013, doi: 10.1021/am4032295.
[32] T. C. Boire, M. K. Gupta *et al.*, "Pendant allyl crosslinking as a tunable shape memory actuator for vascular applications," *Acta Biomater*, vol. 24, pp. 53-63, Sep 2015, doi: 10.1016/j.actbio.2015.06.004.
[33] H. Sun, L. Mei *et al.*, "The in vivo degradation, absorption and excretion of PCL-based implant," *Biomaterials,* vol. 27, no. 9, pp. 1735-40, Mar 2006, doi: 10.1016/j.biomaterials.2005.09.019.
[34] S. H. Ajili, N. G. Ebrahimi *et al.*, "Polyurethane/polycaprolactane blend with shape memory effect as a proposed material for cardiovascular implants," *Acta Biomater,* vol. 5, no. 5, pp. 1519-30, Jun 2009, doi: 10.1016/j.actbio.2008.12.014.
[35] J. N. Rodriguez, M. W. Miller *et al.*, "Reticulation of low density shape memory polymer foam with an in vivo demonstration of vascular occlusion," *Journal of the mechanical behavior of biomedical materials,* vol. 40, pp. 102-114, 2014.
[36] T. L. Landsman, R. L. Bush *et al.*, "Design and verification of a shape memory polymer peripheral occlusion device," *Journal of the mechanical behavior of biomedical materials,* vol. 63, pp. 195-206, 2016.
[37] A. Lendlein and O. E. C. Gould, "Reprogrammable recovery and actuation behaviour of shape-memory polymers," *Nature Reviews Materials,* vol. 4, no. 2, pp. 116-133, 2019, doi: 10.1038/s41578-018-0078-8.
[38] Y. Pierre Gobin, S. Starkman *et al.*, "MERCI 1: a phase 1 study of Mechanical Embolus Removal in Cerebral Ischemia," *Stroke,* vol. 35, no. 12, pp. 2848-2854, 2004.
[39] J. Hartman, W. Small *et al.*, "Embolectomy in a rabbit acute arterial occlusion model using a novel electromechanical extraction device," *American journal of neuroradiology,* vol. 28, no. 5, pp. 872-874, 2007.
[40] W. Small Iv, T. S. Wilson *et al.*, "Laser-activated shape memory polymer intravascular thrombectomy device," *Opt. Express,* vol. 13, no. 20, pp. 8204-8213, 2005/10/03 2005, doi: 10.1364/OPEX.13.008204.
[41] A. Muzaffar, K. Deshmukh *et al.*, "Shape Memory Polymer Composites in Biomedical Field," in *Polymer Nanocomposites in Biomedical Engineering*, K. K. Sadasivuni, D. Ponnamma, M. Rajan, B. Ahmed, and M. A. S. A. Al-Maadeed Eds. Cham: Springer International Publishing, 2019, pp. 299-329.
[42] A. Lendlein, M. Behl *et al.*, "Shape-memory polymers as a technology platform for biomedical applications," *Expert Rev Med Devices,* vol. 7, no. 3, pp. 357-79, May 2010, doi: 10.1586/erd.10.8.
[43] W. Zhao, L. Liu *et al.*, "Adaptive repair device concept with shape memory polymer," *Smart Materials and Structures,* vol. 26, no. 2, p. 025027, 2017.
[44] M. Ahmad, J. Luo *et al.*, "Feasibility study of polyurethane shape-memory polymer actuators for pressure bandage application," *Science and technology of advanced materials,* vol. 13, no. 1, p. 015006, 2012.

NOMENCLATURE

T : Temperature, ^{o}C
T_{trans} : Transition temperature, ^{o}C
σ : Stress, Nm^{-2}
ε : Strain
ε_p : Permanant strain
ε_m : Maximum strain
ε_u : Unloading strain

ICMIEE20-KN10

How Resilient is Our Supply Chain in the Context of COVID-19? – An Emerging Research Area in Supply Chain

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ABSTRACT
Resilience has received a growing importance since its introduction to supply chain literature nearly two decades earlier. Supply chain resilience is the adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost effective recovery, and therefore progress to a post-disruption state of operations – ideally, a better state than prior to the disruption. Ample studies (e.g. empirical, mathematical or theoretical studies) have been conducted to understand the how firms and its supply chain can build resilience in the context of unexpected event (e.g. Tsunami, earthquake, fire, hurricane, etc.). For example – collaboration, redundancy, flexibility, agility, social capital, etc. are well-known antecedents of building supply chain resilience. One of the common trends of supply chain resilience research is that it always focuses on unexpected event that affects either buyer or supplier. As unexpected event is concentrated on a particular geographical location, its negative effect has always been felt on part of supply chain i.e. either on demand side or on supply side. Supply chain researchers never ever discuss how firms and its supply chain partners can built its resilience capability in the context of an event that impact both demand and supply side of a supply chain simultaneously. Such a rare event is COVID-19. COID-19 is a pandemic that negatively influences all the firms and its supply chain globally. As a result, it becomes an important research question for academics and practitioners to investigate to what extent our existing practice of building supply chain resilience is valid in the context of an event that affects the entire supply chain. In this keynote presentation, I will focus on this research question.

Keywords: Resilience, Supply chain, COVID-19.

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ICMIEE20-KN11

Design and Control of Upper Extremity Rehabilitation Robots

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ABSTRACT

Functional impairments of the Upper and/or Lower Extremities (ULE) are common not only among the elderly, but also can occur after a stroke. The World Health Organization reports that stroke affects each year more than 15 million people worldwide. In the US alone, more than 795,000 US people suffer a stroke each year that results in significant deficits in ULE functions and the performance of everyday tasks for those affected. The problem is further compounded by the constantly growing number of such cases. It is estimated that about two-thirds of the stroke survivors incur acute arm impairment. Therefore, one of the challenging aspects of stroke rehabilitation is upper extremity intervention. There is mounting evidence that functional recovery can occur well into the chronic stages of stroke. Late improvements may be attributable to sensorimotor learning and adaptive plasticity in the remaining cortical and subcortical brain tissue. On the other hand, the literature review reveals that the aged population also significantly loses arm and hand function. Thus, there is a pressing need to develop better treatment/therapeutic approaches to decrease the effects of disability due to stroke/geriatric disorders.

The current standard for treatment of upper extremity dysfunctions resulting from a stroke/geriatric disorders is personalized therapy with an OT (involves a large time commitment on the part of the OT, and the treatment duration is very long). Unfortunately, there is a consistent shortage of qualified therapists/clinicians both in developing and developed countries. Therefore, an alternative to conventional treatments/interventions is essential. Past research has shown that intensive movement therapy of the affected extremity, incorporating functional tasks where feedback is provided may lead to improved functions. These key elements of motor learning need to be integrated in rehabilitation paradigms and this can be accomplished through rehabilitation robotics.

To rehabilitate individuals with upper-limb dysfunctions, we have developed end-effector type and exoskeleton type therapeutic robots. The exoskeleton type robot, named Smart Robotic *Ex*oskeleton (SREx) is comprised of a shoulder motion support part, an elbow and forearm motion support part, and a wrist motion support part. It is designed to be worn on the lateral side of the upper limb in order to provide naturalistic movements of the shoulder (i.e., vertical and horizontal flexion/extension, and internal/external rotation), elbow (i.e., flexion/extension), forearm (i.e., pronation/supination), and wrist joint (i.e., radial/ulnar deviation, and flexion/extension). Our end-effector type robot, named Intelligent Therapeutic Robot (iTRob, V.1), composed of 2DoF specially designed for the individuals who are not able to use exoskeleton robot.

The SREx was modeled based on the upper-limb biomechanics; it has a relatively low weight, an excellent power/weight ratio, can be easily fitted or removed, and is able to effectively compensate for gravity. The exoskeleton was designed for use by typical adults, whereas the iTRob was designed for use by children, adults, and/or elderly individuals. The kinematic models of the robots were developed based on modified Denavit-Hartenberg notations, and Newton-Euler formulation was used in dynamic modeling. The control architecture was implemented on a field-programmable gate array (FPGA) in conjunction with a real-time PC. Nonlinear control techniques (model-based and adaptive controller) were used to maneuver the robots to provide active and passive arm movement therapy.

In experiments, typical rehabilitation exercises for single and multi-joint movements (e.g., reaching) were performed. Experimental results show that the developed therapeutic robots can effectively perform passive and active rehabilitation exercises for shoulder, elbow, and wrist joint movements.

Keywords: Exoskeleton Robot, End-effector type Robot, Upper-Limb Dysfunctions, Rehabilitation, Nonlinear controls.