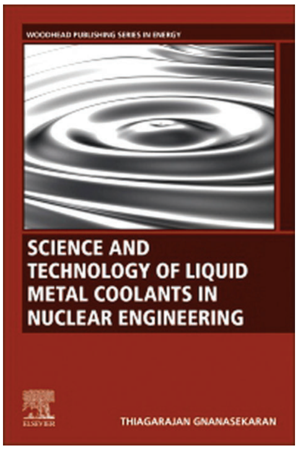
BOOK REVIEW



Science and Technology of Liquid Metal Coolants in Nuclear Engineering, 1st Edn. Thiagarajan Gnanasekaran. Woodhead Series, Elsevier, Cambridge, USA. 2022. 562 pages. Price: US$ 245. Paperback ISBN: 9780323951456.

Liquid Metals Handbook (1954), edited by Richard N. Lyon, appears to be the earliest publication on liquid metal technology[1]. This book has looked at the properties of sodium (Na), sodium potassium alloy (NaK), lead and bismuth, which find application in the nuclear and metallurgical industry. It has touched upon the physical, chemical properties, corrosion mechanisms and gave a flavour of sodium heat exchangers, pumps, instrumentation, etc. With Na and NaK gaining importance for application in fast reactors, a supplement volume of the book on sodium and NaK was edited by Carey B. Jackson. It was brought out in 1955 (ref. 2).

In June 1971, President Richard M. Nixon sent to the U.S. Congress a comprehensive energy message proposing a programme to ensure an adequate supply of clean energy for the years ahead. The message stated, 'Our best hope today for meeting the Nation's growing demand for economical, clean energy lies with the fast breeder reactor'. Sodium had been chosen as the coolant for the Liquid Metal Fast Breeder Reactor (LMFBR) because of its good technical characteristics, including its excellent nuclear and heat-transfer properties, large heat capacity, low vapour pressure, and freedom from corrosion in the absence of air and water. The experience gained over many years of use of sodium as a reactor coolant in the USA has provided the base for the present extensive research and development programmes.

The reactor heat-transfer agent, sodium, is a vital component in the LMFBR system, and its reliability, as well as the reliability of sodium components and sodium systems, should be unquestionable. Sodium must always be compatible with the materials it contacts, retain its heat-transfer characteristics, and remain free of impurities to the extent necessary to prevent blocking of flow passages, prevent corrosion, and allow for free movement of mechanisms in sodium or the cover gas. The impurities content of sodium (including fission products) can be maintained within predetermined levels. The LMFBR operations and maintenance personnel must handle it, store it, clean it off equipment, keep it liquid when needed, and prevent it from contacting air and water. If inadvertent leakages occur, they must be able to minimize the reactions and control the subsequent events. Experiences to date have confirmed that sodium systems and components must and can be designed for ease of accessibility, inspection, replacement and repair. The many complex problems involved in developing and using sodium and sodium components and systems require a disciplined engineering approach and the application of strong quality-assurance measures to resolve them.

In five volumes, the *Sodium–NaK Engineering Handbook* (1972) by O. J. Foust[3] was the first effort to centralize the knowledge gained and provide guidelines and information helpful in designing, engineering, and developing sodium systems and their components and developing sodium technology. This handbook has covered experiences gained in the Experimental Breeder Reactor No. 2, the Enrico Fermi Fast-Breeder Reactor, the Southwest Experimental Fast Oxide Reactor, the Hallam Reactor, the Sodium Reactor Experiment, the many sodium test facilities in USA, RAPSODIE and Phenix in France, Prototype fast reactor (PFR) in UK and test facilities. This book was the best compilation at a time when many developing countries had embarked on the LMFBR program. This book covered sodium chemistry and physical properties (vol. I, 1972), sodium flow, heat transfer, intermediate heat exchangers and steam generators (vol. II, 1976), sodium systems, safety, handling, and instrumentation (vol. III, 1978), sodium pumps, valves, piping, and auxiliary equipment (vol. IV, 1978), and sodium purification, material, heaters, coolers, and radiators (vol. V, 1979). Though the volumes were published in the 1970s, they only contain the information up to 1968.

In the 1980s, two books, one by C. C. Addison (1984) and the other by H. U. Borgstedt and C. K. Mathews (1987), were only on the chemistry of liquid alkali metals. A handbook providing data on lead and lead–bismuth eutectic alloy (*Handbook on Lead–bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal Hydraulics, and Technologies*) was published in 2015 by OECD/NEA. However, this handbook does not discuss the details of various instruments used in heavy liquid metals and their principles.

In 2015, a book on *The Thermophysical Properties of Metallic Liquids* by Takamichi Iida and Roderick I. L. Guthrie was published by Oxford University Press. The book consists of two volumes, presenting the physics of thermophysical properties in the first and predictive models for estimating these properties in the second. Volume 1 takes the reader from the atomic level to the macro-region correlating structure with properties, providing a fundamental understanding. Volume 2 is a boon to engineers in choosing reliable data and models.

A database of the main thermo-physical properties of liquid sodium, lead, LBE and bismuth (as a component of LBE) reported in the open literature (such as characteristic temperatures, pressures and latent heats, surface tension, density, sound velocity, compressibility, heat capacity, enthalpy, viscosity, thermal and electrical conductivity), etc. has been reported by Sobolev (Scientific Report SCK-CEN-BLG-1069 Database of thermophysical properties of liquid metal coolants for GEN-IV, published by SCK•CEN Belgium in 2010). It gives best-fit correlations for different thermophysical properties.

Since 1968, much sodium technology development has occurred in different countries like France, India, Russia, Japan and China. However, the information generated by the research lies scattered as journal papers, reports, patents, and other publications, and nowhere are these data consolidated in a single book. For an efficient design and the operation and utilization of a liquid metal system, an understanding of all these technologies, starting from the manufacture of liquid metals, its utilization in reactor systems, its removal and finally disposal, are required besides safe handling and reliable instrumentation. Also, basic knowledge of the thermophysical and chemical properties of liquid metals and the correlations among them is needed.

The present book under review by T. Gnanasekaran, from India, has meticulously consolidated all research and developments in thermophysical chemical and nuclear properties, handling and operations, pumps, and instruments, corrosion, and mass transfer of liquid metal coolants. The major emphasis has been on the pumps and instrumentation, wherein major developments have occurred.

Chapter 1 deals with the thermophysical properties of liquid metals in general emphasizing their microscopic origin. The structure and cohesive energy of liquid metals are discussed in detail. The viscosity and surface tension of liquid metals and their correlation to cohesive energy are brought out. The phenomenon of wetting of solids by liquids and the role of bonding in solids and liquids are brought out with special emphasis on liquid metal wetting. The origin of high electrical and thermal conductivities of metallic solids are discussed, and the changes that occur in these properties when the metallic solids transform into liquids are brought out considering the structure of the liquid metals. The vapour pressure and heat capacity of liquid metals are also discussed.

Electromagnetic pumps and mutual inductance-based detectors are used in liquid metal coolant circuits, which need a good understanding of electrical conductivity and magnetic permeability, and the author has successfully brought out the basics needed. After discussing all these properties of liquid metals in general, the choice of coolants for fast breeder and fusion reactors and accelerator-driven systems are discussed in detail. The author has devoted separate sections to heavy metals (Lead, Lead Bismuth Eutectic, LBE) that are candidate coolants for future fast reactors. A good portion has been devoted to accelerator-driven systems employing liquid metals. This is a valuable addition for researchers.

Wetting of metallic surfaces by liquid metals has a major effect on the design of heat transfer phenomena besides instrumentation. The surface tension of a liquid metal determines the wetting of a solid by it and influences heat transfer characteristics and corrosion phenomena. The basics of the wetting process have been nicely presented.

In short, this is a well-written, cohesive chapter on the thermophysical properties of liquid metals.

Chapter 2 deals with industrial methods of manufacturing liquid metal coolants (Li, Na, K, Pb, NaK alloys, Pb and LBE) and their chemical properties. Methods to prepare these metals in a very pure state are also outlined. Reactions of these candidate coolants with constituents of air, water, hydrogen and carbon-bearing materials, which need to be understood for the safe handling of liquid metals, are dealt with in detail. Kinetics of dissolution and precipitation of non-metallic impurities such as oxygen and hydrogen in liquid metals, which are needed for the design of effective purification of liquid metal coolants, are dealt with in detail.

Chapter 3 deals with the safe handling of liquid metal coolants and the design of purification systems to effectively remove radioactive and non-radioactive impurities. It is nice that the author has dealt with handling sodium, lithium, NaK, Pb and LBE in separate sections, as their requirements vary. Coming to cold traps, the purification process involves both heat and mass transfer phenomena. Simulation models to predict the area of oxide and hydride deposits in cold traps have been developed. Simulation helps in better optimization and reduces testing. While the author has referred to articles on this aspect for the interested reader, the reviewer feels he could have added a brief outline in the text.

Although liquid metal circuits have systems to monitor and control the level of dissolved non-metallic impurities, there is a need to identify any inadvertent introduction of metallic and non-metallic impurities into the system while in operation. This requires an efficient arrangement to get a representative sample from the liquid metal circuit and suitable methods to chemically analyse the impurities at the appropriate concentration levels. The author has brought out details of sampling methods in sodium and heavy liquid metals. This aspect is beneficial for the practical system engineer.

Fires due to leaks of liquid alkali metals and methods to extinguish them, as well as disposal of sodium metal wastes on small and large scales, are described. Sodium removal from components before maintenance must be carried out safely. Safe methods of sodium cleaning of components besides removal of residual sodium have been nicely brought out. An accident related to the use of ethyl carbitol for cleaning residual sodium in large vessels has been highlighted.

Experiences of cold trap regeneration in different countries have been brought out. Perhaps, the author could have added the aspect of Radiographic examination of deposits in the cold traps.

Chapter 4 deals with the pumps and instruments required to safely and reliably operate heat transfer circuits with liquid metals. Centrifugal and electromagnetic pumps used for circulating liquid metal in these circuits are described in detail. Instruments for detecting the levels and flow of liquid metals, as well as ultrasonic transducers for viewing components immersed in liquid metals are described in depth. Methods to detect liquid alkali metal leaks and for online monitoring of impurities in liquid metal circuits are also discussed in detail. Theoretical principles of operation of these pumps and instruments are explained.

While centrifugal pumps have been used for the main sodium circuits, electromagnetic pumps are used in auxiliary circuits like fill, drain and purification. This topic has been well covered. Perhaps the author could have added the development of sodium immersible pumps. These are needed in case it becomes necessary to pump out the primary sodium in the reactor to carry out any repairs.

The author has given enough exposure to the instrumentation needs of an LMFBR. Level and flow measuring instruments, besides leak detectors, have been well presented. The sodium ionization detector (SID), which can detect nanograms/cc of sodium aerosols, has been explained. The detection of hydrogen in sodium and argon due to water leak into sodium has been well covered. The description of the basis of electrochemical and diffusion meters for hydrogen detection is extensive and a new researcher can get a good background on the subject. The data on corrosion in liquid metals has been adequately covered.

The sodium scanning of components using ultrasonics has made a lot of headway in the past decades, and the author has covered this aspect. Maybe the author could have touched upon the *scanner's utility* in actual conditions in the FBTR reactor in India and referred to the corresponding literature for the interesting reader to highlight its importance.

Chapter 5 dwells on corrosion and mass transfer processes in liquid metal coolant circuits. It first deals with the driving forces for this corrosion and mass transfer phenomenon. Since the structural materials used are dependent on the coolant employed, the corrosion and mass transfer phenomena are unique for each system. The observed corrosion phenomenon in each liquid metal and structural material and the underlying mechanisms are described.

This chapter also deals with the experimentally observed characteristics of wetting of surfaces of the structural materials by liquid metals, which is the prerequisite for corrosion and mass transfer processes in the system to set in. For proper functioning of the ultrasonic under sodium scanner, the surface of the metal plate exposed to liquid metal should be completely wetted, and the author has explained the conditions to ensure good wetting. Wetting is also important for properly measuring level and flow meters besides operating electromagnetic pumps.

Epilogue

The author must be complimented for bringing out a set of areas for further development in liquid metal technology based on his experience of three decades.

General

Perhaps, the author did not get into the component design aspects, as not many changes have taken place. The sodium-to-sodium heat exchanger design has remained unchanged except for small design improvements. However, the steam generator designs in different reactors were quite different. The author could have added an annexure on the description of the components of an LMFBR and briefly described the role of each component with some description. It would have given a sense of a complete handbook. While the author has introduced basic concepts of heat transfer and given correlations for liquid metals, it would have been better for completion's sake to have added a table of heat transfer correlations on the water/steam side. This would *give the reader* a complete picture of the heat transfer phenomena in the steam generator.

As indicated in the Foreword by Christian Latge, who is an authority in sodium technology from CEA France, Gnanasekaran has brought out a comprehensive book discussing all the properties of liquid metals, including their microscopic origins and discussing the basic principles and operational experience of special instruments and equipment needed for operating liquid metal systems.

Overall, this book is an invaluable asset for researchers and practising technologists alike. It provides comprehensive insights into the field of liquid metals and would greatly benefit entry-level scientists or engineers who are embarking on projects involving this fascinating area of study. Therefore, it is strongly recommended that this book be made widely accessible to all institutional libraries.

1. Lyon, R. N. (ed.), *Liquid Metals Handbook*, The Atomic Energy Commission, The Bureau of Ships and Department of Navy, USA, 1954; https://ia802306.us.archive.org/32/items/liquid-metals-handbook-1954/LiquidMetals-Handbook_1954.pdf
2. Jackson, C. B. (ed.), *Liquid Metals Handbook-Sodium-NaK Supplement (TID-5277)*, The Atomic Energy Commission and The Bureau of Ships, Department of The Navy, 1955; https://ia802308.us.archive.org/9/items/liquid-metals-handbook-na-na-ksupplement-1955/LiquidMetalsHandbook_Na-NaKSupplement_1955.pdf
3. Foust, O. J. (ed.), *Sodium–NaK Engineering Handbook*, in 5 volumes, Prepared under the auspices of the Division of Reactor Development and Technology United States Atomic Energy Commission, Gordon and Breach, Science Publishers, Inc., New York, London, Paris; https://www.osti.gov/servlets/purl/46-31555

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