Lecture Notes in Electrical Engineering 1118

Sanjay Yadav
Yogendra Arya
Nor Asiah Muhamad
Karim Sebaa *Editors*

Energy Power and Automation Engineering

Select Proceedings of the International Conference, ICEPAE 2023

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Energy Power and Automation Engineering

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Preface

Titled with *Lecture Notes in Electrical Engineering* and available on latest research progress of electrical engineering, this paper volume gathers a bunch of papers collected from *2023 4th International Conference on Energy Power and Automation Engineering (ICEPAE 2023)*, held in hybrid mode at Zhejiang University of Water Resources and Electric Power (Nanxun Campus), China, during June 9–11, 2023.

The Conference, attended by more than 130 delegates around the globe, was hosted by Yan He, Director of the International Cooperation and Exchange Office of Zhejiang University of Water Resources and Electric Power, and Dr. Chuanhui Zhu. In the opening ceremony speech, Bo Zhao, Vice President of Zhejiang University of Water Resources and Electric Power, expressed his heartfelt thanks and sincere welcome to all academicians, experts and scholars who spared their precious time to attend the Conference. In the keynote speech part, Professor Guohai Liu from Jiangsu University, China, Professor Jinfeng Gao from Zhejiang Sci-Tech University, China, Professor Jinfeng Liu from University of Alberta, Canada, and other keynote speakers made wonderful academic reports on international frontier hot spots. Apart from keynote speeches, oral and poster presentation part were also held and displayed by various scholars, leading to a warm atmosphere of academic discussion.

We received a number of research article submissions in the Conference. After rigorous review by related top experts and review rebuttal process, various excellent papers were accepted and included in this paper volume. These papers cover mainly three parts of the conference: 1. Energy Conversion and Utilization and Thermal Power Engineering, 2. Mechanical Manufacturing and Electrical Automation Control and 3. Mechatronics and Remote Sensing Signal Monitoring. The research works of this volume can promote the development of energy power and automation engineering and thereby enhance scientific information interchange between scholars from top universities, research centers and high-tech enterprises working all around the world.

Featuring the most cutting-edge research directions and achievements related to energy power and automation engineering, this conference provided the most comprehensive research in the related fields and a more comprehensive understanding of the latest results of cross research in this field. Meanwhile, it also helped researchers and engineers to understand the research frontier, as well as discover the solutions to engineering problems.

We would like to acknowledge the authors for their contributions and the reviewers for their time to review the submissions rigorously. We are thankful to all the committee members and advisors of this volume. Finally, this volume presents some of the latest researches in the fields of energy power and automation engineering and is believed to be beneficial to develop relevant subjects. We hope that it will serve as a reference for researchers and practitioners in academia and industry related to energy power and automation engineering.

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Sanjay Yadav obtained his master's degree in science (M.Sc.) in 1985 and his Ph.D. degree in Physics in 1990. Presently, he is working as Editor-in-Chief (EIC) of the MAPAN: The *Journal of Metrology Society of India.* He is also Vice President of the Metrology Society of India (MS), New Delhi, as well as Vice President of the Ultrasonic Society of India (USI), New Delhi. He is Former Chief Scientist and Head of the Physico Mechanical Metrology Division of NPL and also Former Professor at the Faculty of Physical Sciences, Academy of Scientific and Innovative Research (AcSIR), HRDG, Ghaziabad. He has taught "Advanced Measurement Techniques and Metrology" courses, taken practical classes and supervised graduate, master and Ph.D. students since 2011. He is Recipient of several awards and scholarships of National and international repute. He has significantly contributed to the field of pressure metrology, biomedical instrumentation, ultrasonic transducers and instrumentation systems. His current research interests include research and developmental activities in physicomechanical measurements; establishment, realization, maintenance and up-gradation of national pressure and vacuum standards; dissemination of national practical pressure scale to users through apex level calibration, training and consultancy services; inter-laboratory comparisons, proficiency testing program and key comparisons; implementation of quality system in the laboratory as per ISO/IEC 17025 standard and finite element analysis (FEA) and Monte Carlo simulations for pressure balances. He has published more than 450 research papers in national and international journals of repute and conferences, 20 books, 14 patents and copyrights, supervised eight PhDs (another five in waiting) and drafted several projects, scientific and technical reports, documents and policy papers.

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Karim Sebaa received his Electrical Engineering Degree and Magister in High Voltage and Power Systems from Ecole Nationale Polytechnique, Algiers, Algeria in 1998 and 2000, respectively. From September 2007 to March 2009, he was Visiting Student at Suplélec French. Since 2003, he has joined the University of Medea, Algeria, where presently he is currently Full Professor of Power Systems. His research interests include power system dynamics, distribution power systems and green energy penetration into power systems. He has authored and co-authored more than 30 technical papers comprising of journals and conference proceedings. He also has contributed to articles for many conferences and journals published by IEEE, Elsevier and others.

Energy Conversion and Utilization and Thermal Power Engineering

Analysis of the Thermal–Hydraulic Characteristics of Supercritical CO_2/Kr Mixtures in the Straight-Channel Printed Circuit Heat Exchanger

Ya-Nan Ma and Peng Hu

Abstract The supercritical carbon dioxide recompression Brayton cycle (SCO_2RBC) has attracted much attention as one of the most promising thermal power conversion systems. As the component with the largest volume and quantity in the cycle, the heat exchanger has a crucial impact on the cycle efficiency. Printed circuit heat exchanger (PCHE) is widely utilized as regenerator and precooler in the Brayton cycle. CO_2/krypton has shown great potential for development as the working fluid of Brayton cycle. In this work, PCHE is analyzed as the high-temperature regenerator for Brayton cycle with CO_2/krypton mixtures as the heat transfer fluid in both hot and cold channels. Thermal properties of CO_2/Kr vary with temperature, and mass fraction of Kr is explored. The thermal–hydraulic characteristics of S-CO_2/Kr mixture flow in straight-channel PCHE are investigated. The effects of krypton mass fraction, channel diameter, and Reynolds number on heat transfer and friction features are discussed via numerical analysis. The results show that the Nusselt number of cold and hot channel increases by 1.09 and 0.87% when the molar fraction of krypton varies from 0 to 0.25 while the change of Fanning friction factor can be neglected. The channel diameter and Reynolds number have important effects on the thermal–hydraulic performance of cold and hot channels. New correlations are developed for the flow and heat transfer performance of CO_2/krypton (mass fraction 0.75/0.25) PCHEs with errors of less than ± 5%.

Keywords Supercritical Brayton cycle · CO_2-based mixtures · Printed circuit heat exchanger · Thermal–hydraulic characteristics

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1 Introduction

Compared to traditional thermal power conversion systems, the supercritical CO_2 Brayton cycle (SCO_2BC) has higher efficiency, more compact structure and lower cost [1]. The bulk and efficiency advantage of the SCO_2 Brayton cycle come from the fact that CO_2 behaves almost like an incompressible fluid with high density, high thermal conductivity, low viscosity, and high diffusion coefficient near its critical point (30.98 °C and 7.38 MPa) [2]. The critical point acts as a limitation of the lowest operating condition of the cycle. The critical point of CO_2 can be regulated by mixing with other gases, thus changing the minimum operating conditions of the Brayton cycle. Using CO_2-based binary mixtures as the working fluids is a way to improve the performance of the Brayton cycle [3–5]. Ma et al. [5] carried out thermo-economic analysis and multi-objective optimization on SBC with CO_2-based mixtures. It was shown that compared with the SCO_2BC, the supercritical CO_2/krypton (Kr) cycle had a large increase in cycle efficiency but less cost increase. The supercritical CO_2/Kr Brayton cycle shows better thermodynamic performance than SCO_2BC and has great potential for development.

Printed circuit heat exchanger (PCHE) is widely utilized as regenerator and precooler in the Brayton cycle because of its compact structure, high efficiency, high temperature and pressure resistance, and other advantages [6]. At present, most researches on the thermal–hydraulic characteristics in PCHE focus on the structure, operating conditions [7, 8], and working fluid [9, 10]. Zhou et al. [11] took CO_2/propane mixture as the working fluid of Brayton cycle. The thermal and hydraulic characteristics of CO_2/propane mixtures with different concentrations in straight-channel PCHE were investigated by numerical analysis. It can be found that CO_2/propane mixture as a heat transfer fluid has lower pressure drop and higher heat transfer coefficients. In our previous work [5], CO_2/Kr has shown great potential for development as the working fluid of SBC. There is a lack of research and correlations on the supercritical CO_2/Kr (S-CO_2/Kr) mixture flow in PCHE. In this work, the thermal–hydraulic characteristics of S-CO_2/Kr mixture flow in straight-channel PCHE are investigated and compared. The effects of the mass fraction of Kr, the geometric parameters of the channel, and Reynolds number on the thermal–hydraulic performances of PCHE are shown in the numerical analysis. Based on the numerical results, correlations for Nusselt number and Fanning friction factor on Reynolds number are proposed, respectively. The following are the main originality of this paper:

1. PCHE is analyzed as the high-temperature regenerator (HTR) for supercritical Brayton cycle with outlet pressure up to 20 MPa and inlet temperature up to 700 K.
2. The study is carried out for S-CO_2/Kr mixture as the working fluid in both hot and cold channels.
3. The global Fanning friction factor and Nusselt number correlations are proposed. This study provides guidance for the design of PCHE and its application in the Brayton cycle.

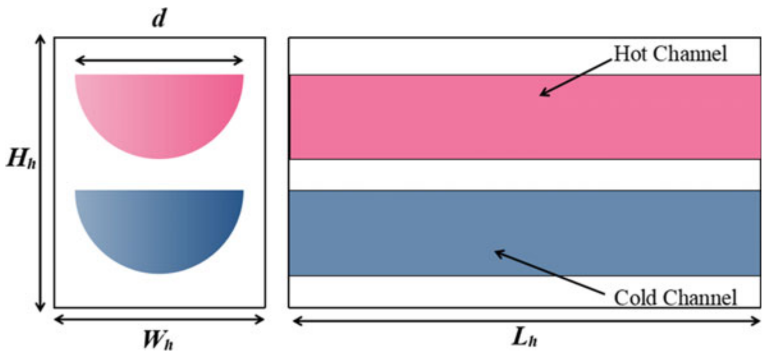

Fig. 1 Schematic diagram of PCHE geometric model

Table 1 Computational domain size parameters

Parameters	Symbol	Size (mm)
Channel diameter	d	1.4–2
Height of the heat exchanger unit	H_h	3.2
Length of the channel	L_h	200
Width of the heat exchanger unit	W_h	2.5

2 Model and Numerical Method

2.1 Physical Model and Boundary Condition

The physical model of PCHE is shown in Fig. 1. A double-channel straight PCHE units are chosen for numerical simulation because PCHE consists of a large number of heat exchanger units arranged periodically. Table 1 shows the geometric size parameters of PCHE. The setting of model parameters refers to Refs. [11, 12], which is the commonly used size of heat transfer unit of straight-channel PCHE at present. The solid material is Inconel 617 alloy with constant physical properties. Ansys Fluent 19.0 is utilized for numerical simulation in this work. The structured mesh of geometric model is generated by Ansys ICEM. The velocity inlet boundary conditions and the pressure outlet boundary conditions are adopted at inlet and outlet of the cold and hot channels. Supercritical CO_2/Kr is used as the working fluid for both channels.

2.2 Mathematical Model

The heat transfer coefficient h of the fluid can be defined as follows:

$$h = \frac{q_w}{T_b - T_w} \tag{1}$$

where T_w is the area weight average wall temperature, and T_b is the mass weighted average bulk temperature. The hydraulic diameter of the channel D_h can be calculated by

$$D_h = \frac{\pi d}{2(\pi/2 + 1)} \tag{2}$$

The Reynolds number and Prandtl number are determined as:

$$\text{Re} = \frac{\rho v D_h}{\mu} = \frac{G D_h}{\mu} \tag{3}$$

$$\text{Pr} = \frac{\mu c_p}{\lambda} \tag{4}$$

where dynamic viscosity μ, thermal conductivity λ, density ρ, and specific heat capacity c_p are based on bulk temperature T_b. v represents the velocity of the fluid.

The Nusselt number is calculated by

$$\text{Nu} = \frac{h \cdot D_h}{\lambda} \tag{5}$$

The accelerated pressure drop, the frictional pressure drop, and Fanning friction factor f of the channel can be expressed from Eqs. (6) to (8), and the subscripts in and out mean inlet and outlet.

$$\Delta P_{ac} = \rho_{out} v_{out}^2 - \rho_{in} v_{in}^2 \tag{6}$$

$$\Delta P_f = \Delta P - \Delta P_{ac} \tag{7}$$

$$f = \frac{\Delta P_f \cdot D_h}{2L\rho v^2} \tag{8}$$

2.3 Working Fluid Selection

Krypton is selected to mix with CO_2 in this study due to its great potential for application in the Brayton cycle shown in previous studies. The variation curves of the critical temperature and pressure of the CO_2/Kr mixtures with the increase of Kr mass fraction are shown in Fig. 2. According to the analysis in Ref. [5], the critical temperature of the working fluid was 5 K higher than the ambient temperature. The

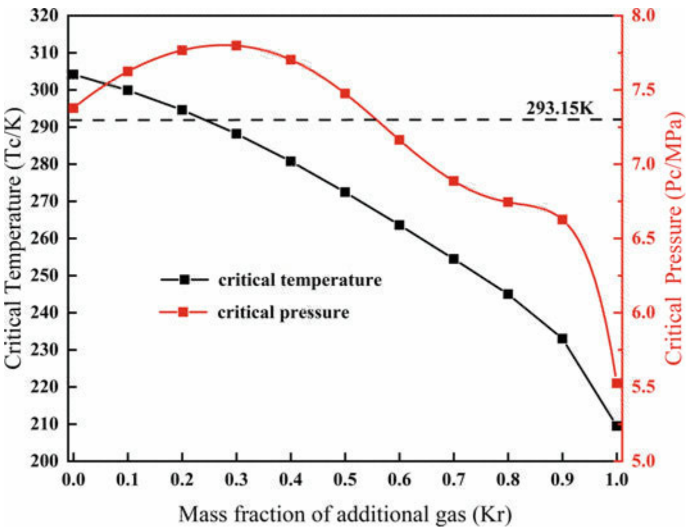

Fig. 2 Critical pressure and temperature of the CO_2/Kr mixtures with different mass fraction of Kr

study is conducted under the assumption that ambient temperature value is higher than 288 K. Therefore, the mass fraction of Kr is studied in the range of 0–0.25.

3 Results and Discussions

3.1 Influence of Mass Fraction of Kr on Flow and Heat Transfer Characteristics

The trends of thermal properties changing with temperature in the range of 400–600 K are shown in Fig. 3. The density ρ and the viscosity μ increase as the mass fraction of Kr increases which means better compressibility. The specific heat capacity c_p and thermal conductivity λ decrease with the increasing mass fraction of Kr. As the temperature increases, the thermal conductivity increases linearly which means greater heat transfer performance of working fluids.

The inlet temperatures of the cold and hot fluids are 480 K and 700 K, respectively. The outlet pressure of the hot and cold channel is kept at 8.2 and 20 MPa. Figure 4 shows the Nusselt and friction factor variation of straight-channel PCHE with the mass fraction of Kr for hot and cold working fluid. When the mass fraction of Kr changes from 0 to 0.25, the Nusselt number of hot and cold channels increases by 1.06% and 0.87%, respectively, the friction factor increases first and then decreases, and the numerical change is very small. This result can be attributed to the decrease of thermal conductivity and specific heat and the increase of density of the working

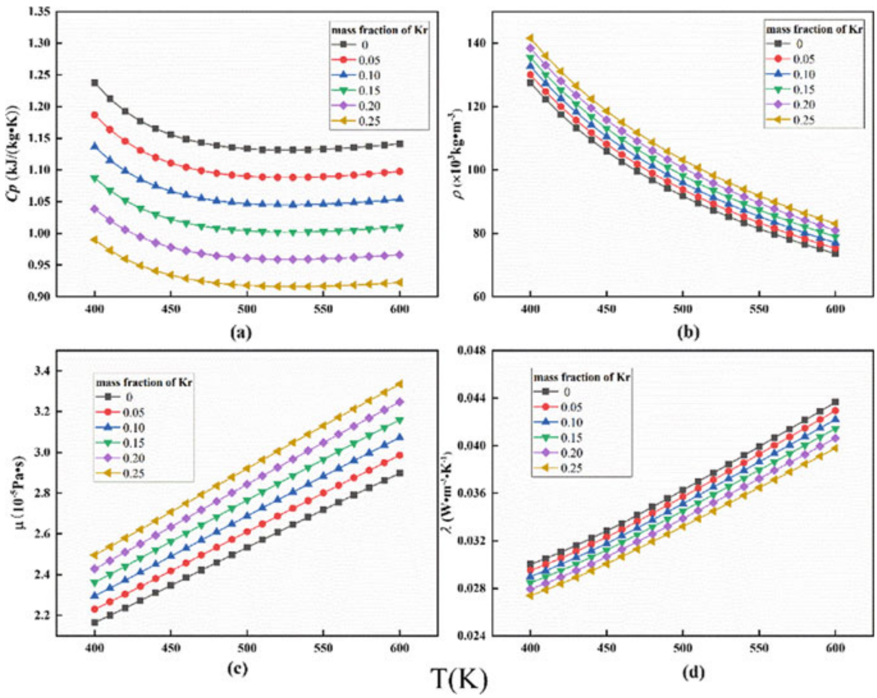

Fig. 3 Thermal properties of CO_2/Kr vary with temperature and mass fraction of Kr

fluid due to the addition of Kr. The reduction of specific heat makes the heat transfer decrease, but the thermal conductivity also decreases, so the Nusselt number shows an upward trend. With the addition of Kr, the heat transfer performance of PCHE is slightly enhanced. Taking Nusselt number as the heat transfer evaluation standard, the addition of Kr is beneficial to the heat transfer efficiency.

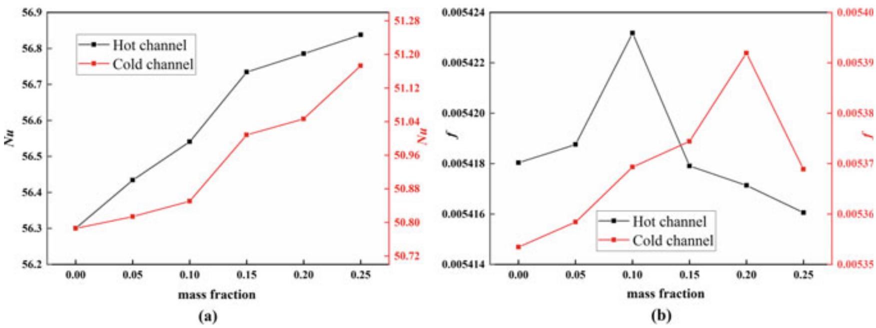

Fig. 4 **a** Nusselt number, **b** fraction factor of fluid versus the mass fraction of Kr

3.2 Influence of Channel Diameter and Reynolds Number on Flow and Heat Transfer Characteristics

The geometric models of four different channel diameters are established, respectively, 1.4, 1.6, 1.8, and 2 mm, while $H_h/2$ and $(W_h - d)$ are kept constant. Using CO_2/Kr mixture with mass fraction of 0.75/0.25 as the working fluid, the inlet mass flow rate of cold and hot working fluids is adjusted so that the corresponding inlet Reynolds number is 5500, 11,000, 16,500, 22,000, and 27,500, respectively. In Fig. 5a, as the Re increases, the Nusselt number generally shows a trend of linear growth. Because when the Reynolds number increases, the fluid velocity increases, the boundary layer thickness becomes thinner, and the heat transfer is enhanced. Figure 5a shows that the increase in channel diameter will reduce Nusselt number, thus negatively affecting the growth of heat transfer efficiency. It can be seen from Fig. 5b that the increase of Re reduces the friction factor and the increase of channel diameter has a positive impact on the flow in the channel. When the diameter of the channel increases, the heat transfer area increases, which promotes the heat transfer. However, the increase of channel diameter will lead to the decrease of velocity, resulting in the decrease of fluid turbulence intensity and fluid disturbance, which will reduce the flow loss but inhibit the heat transfer. When Reynolds number increases, the effect of velocity on friction factor is more significant than that of frictional pressure drop. Therefore, the friction factor gradually decreases with the increase of Reynolds number. When Re is 22,000, the diameter of the hot channel is from 1.4 to 2 mm, and the Nusselt number is reduced by 7.36% while the friction factor is reduced by 8.33%. Larger heat exchangers will result in less pressure loss to some extent increase in cycle efficiency.

3.3 Correlations for Flow and Heat Transfer

Based on the numerical simulation at three hot channel inlet temperatures of 650, 700, and 750 K, the new correlations for Nusselt number and Fanning friction factor are fitted. Figure 6 shows the accuracy of the developed correlations which are shown in Table 2. Nusselt number is positively correlated with Reynolds number, while friction factor is opposite. Higher Reynolds number is instrumental in improving thermal–hydraulic characteristics of PCHE. The prediction deviations of the correlations for Nu_h, f_h, Nu_c, and f_c are less than 2%, 5%, 3%, and 2%, respectively, indicating that the correlations have high accuracy and can be used to predict the flow heat transfer characteristics of supercritical CO_2/Kr fluid with mass fraction ratio of 0.75/0.25 in the PCHE within the Reynolds number range of 5500–27,500.

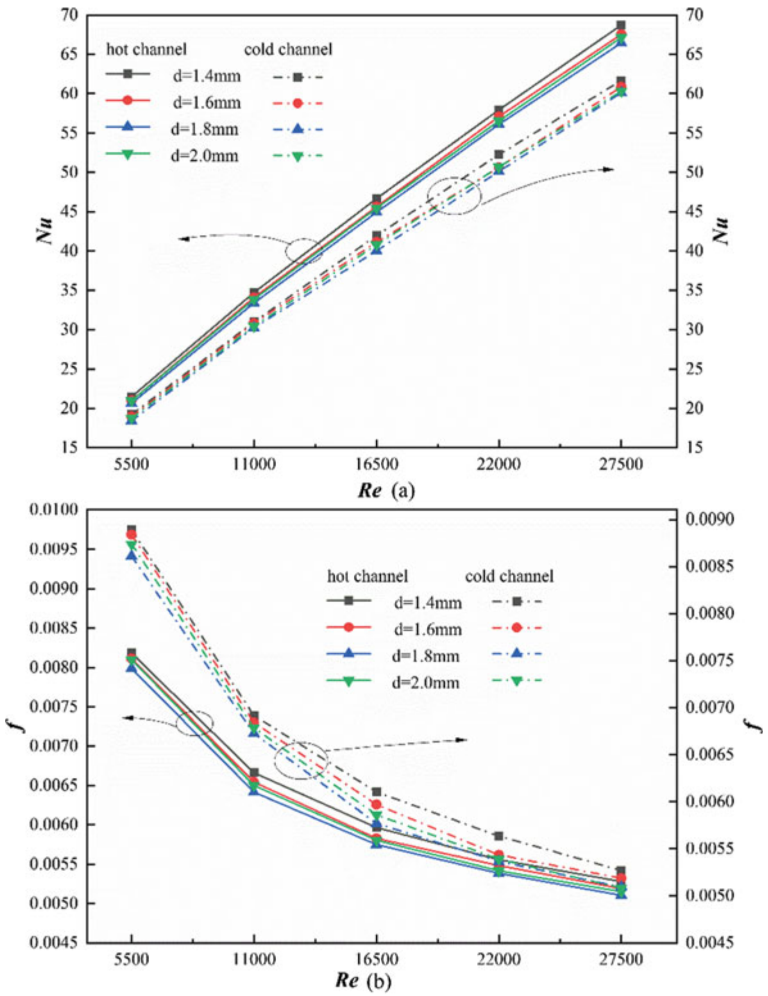

Fig. 5 **a** Nusselt number, **b** fraction factor of fluid versus channel diameters in straight channel for various Reynolds numbers

4 Conclusion

In this work, a straight double-channel PCHE numerical model is established. The thermal and hydraulic characteristics of S-CO_2/Kr mixture flow in straight-channel PCHE are investigated; finally, the correlations for Nusselt number and Fanning friction factor are proposed. The conclusions are obtained as below:

(1) The Nusselt number slightly increases, and the friction factor increases first and then decreases with the increase of the mass fraction of Kr. There is a slightly enhancement in heat transfer of the heat exchanger with the addition of Kr. It