Numerical Research on the Flow Fields in the Power Generation Channel of a Liquid Metal Magnetohydrodynamic System

Peng Lu,* Riliang Fang, Qihang Ye, and Hulin Huang*

Cite This: ACS Omega 2020, 5, 31164−31170

ABSTRACT: The flow fields in the power generation channel of a magnetohydrodynamic system, which uses a mixture of liquid metal as the power generation medium and a low-boiling-point working medium as the carrying medium, were numerically investigated in the present paper. The influences of the magnetic field intensity, void fraction, and bubble diameter were examined, respectively. The results indicate that an increase in the magnetic field intensity will enhance the turbulence intensity and may reduce the stability of the flow fields, whereas increasing the void fraction will contribute to better flow stability in the power generation channel. The effect of the bubble diameter on the flow field stability is negligible in the range of the study. In addition, it is found that the volume fraction of the gas phase exhibits an M-shape distribution by studying the variation of the slip velocity over time. This paper presents our latest findings and will provide a fundamental theory for future design and operation of liquid metal magnetohydrodynamic systems.

1. INTRODUCTION

High-efficiency energy generation technology is currently a major concern due to the rising price of energy, scarcity of fossil fuel resources, and environmental pollution. MHD (magnetohydrodynamic) power generation systems, which are based on Faraday’s law of induction to conductive fluid, can directly convert the kinetic energy of working fluids into electric power. It features high-efficiency conversion, low environmental impact, few mechanical moving parts, etc. It is thus regarded as a feasible and competitive power generation technology that has aroused worldwide attention and interest.

Since the success of the 11.5 kW magnetic fluid power generation test device developed by the United States in 1959, worldwide institutions have invested numerous resources on this subject afterward. The use of liquid metal as the working fluid in magnetohydrodynamic (MHD) generators was considered. A simple model of the Faraday-type generator is developed and used to obtain relations, giving generators terminal voltage, pressure drop, and efficiency. Argonne National Laboratory in the United States first proposed the concept of a two-phase flow magnetic fluid generator, presenting the experimental results of two-phase liquid-metal MHD investigations using circular and rectangular test-section geometries.

The gas/liquid metal magnetohydrodynamic generator (G/ LM-MHD) with the mixture of gas and liquid metal as working fluids shows a promising future due to the recent development of renewable energy technologies, which has caused an upsurge in the research of two-phase flow magnetic fluid power generation. Masaki et al. found that the gas−liquid slip ratio and the MHD pressure drop in the two-phase liquid metal flow under a strong magnetic field are in close relation to the distributions of the gaseous phase and the fluid velocity. Fabris et al. studied the two-phase slip inside the power...
generation channel and obtained an expression for the effect of the speed difference between gas and liquid on the performance of the generator. The results show that the main reason for the decrease in the efficiency of the LMMHD generator is that the two-phase flow changes from a bubble flow to a stirred flow at a higher void ratio, and the slip loss increases rapidly; experiments aimed at improving mixer design by Fabris et al.7–10 demonstrated that a high void fraction (0.8) and low velocity slip ratio (1.2) two-phase homogeneous bubbly mixture can be created. It is expected that such a two-phase mixture can be further expanded in an LMMHD generator while maintaining low-velocity slip.7–10 Yamaguchi et al.11 established a magnetohydrodynamic (MHD) generator model using conductive low melting point gallium alloy. They found that the electric output increases with flow velocity, magnetic strength, and electric conductivity, and the theoretical predictions and numerical results are in good agreement with the experimentally measured data.11 Kobayashi et al. numerically assessed the influence of non-uniform magnetic flux density and connected load resistance on turbulent duct flows in a liquid metal magnetohydrodynamic (MHD) electrical power generator.12 Huang et al. conducted fully-developed three-dimensional numerical simulations of an MHD generator coupling with an outer resistance circuit; in the calculations, two significant non-dimensional parameters Hac and Rec, whose influences on velocity and electromagnetic variables were elaborately discussed, are deduced from the governing equations.13

The previous researches mainly focused on conceptual design, feasibility analysis, and preliminary experiments. There are two kinds of working fluids in a liquid metal magnetohydrodynamic (LMMHD) system, i.e., the liquid metal as the power generation fluid and the low-boiling-point working medium as the carrying fluid. In the power generation channel, the two fluids mix and form a gas–liquid two-phase flow, which is highly complex under the coupling effects of multiple physical fields. The power output and efficiency will consequently be largely influenced by the flow fields inside the channel. Therefore, the present work will examine the flow fields detailedly by revealing the effects of the magnetic field intensity, void fraction, and bubble diameter, respectively.

2. MODELING

The schematic of the power generation channel is depicted in Figure 1, which is a (35 mm) × b (20 mm) × c (200 mm). We assume that: (1) The working medium is incompressible; (2) The enthalpy drop of the two-phase flow is minimal due to the short length of the channel; and (3) The impact of gravity is neglected.

Figure 1. Schematic of the LMMHD power generation channel.
Electric potential equation can thus be deduced from eqs 10–12:

\[ \nabla^2 \phi = \nabla (V \times B) \]  

(13)

Finally, the electric current can be calculated by the Generalized ohm law after solving the electric potential.

2.1.4. Turbulence Model. According to the flow characteristics in the generation channel, the standard \( k-\varepsilon \) model has good precision and convergence. The influence of the magnetic field on turbulence is added to the turbulence equation in the form of source terms, which are respectively \(-\varepsilon_{em}\) and \(-\varepsilon_{em}^k\):

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \mu + \frac{\mu_t}{\sigma_k} \right] \frac{\partial k}{\partial x_i} + G_k - \rho \varepsilon - \varepsilon_{em}^k 
\]  

(14)

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \mu + \frac{\mu_t}{\sigma_\varepsilon} \right] \frac{\partial \varepsilon}{\partial x_i} + C_1 \varepsilon G_k - C_D \varepsilon^2 - \varepsilon_{em}^\varepsilon 
\]  

(15)

where \( G_k \) is the turbulent kinetic energy caused by the velocity gradient, \( \sigma_k \) and \( \sigma_\varepsilon \) are the turbulent Prandtl numbers based on \( k \) and \( \varepsilon \), and \( \mu_t \) is the coefficient of turbulent viscosity.

2.2. Boundary Conditions. Pressure-based solver was used for unsteady computation, with the diffusion term discretized by the central difference format. SIMPLE algorithm was applied to resolve the pressure–velocity coupling equation, with the turbulence term calculated by the standard \( k-\varepsilon \) model. The potential method of MHD module and the UDS transport equation were combined to solve the electrical potential, with the load factor of 0.5.

Velocity-inlet boundary condition was adopted at the entrance of the power generation channel, with inlet velocity of 3 m/s and temperature of 640 K. The pressure outlet boundary condition was employed, with the outlet pressure at 7.5 MPa. In addition, the boundary condition of no-slip velocity was used for the wall surface. The physical properties of liquid sodium and decane are listed in Table 1.

### Table 1. Physical Properties of the Working Media

| physical properties | liquid sodium | decane |
|---------------------|---------------|--------|
| density (kg·m⁻³)    | 868           | 431.7  |
| viscosity (kg·m⁻¹·s⁻¹) | 3 × 10⁻⁴     | 7.1 × 10⁻⁵ |
| electric conductivity (1·Ω⁻¹·m⁻¹) | 1.94 × 10⁴ |        |

3. RESULTS AND DISCUSSION

3.1. Verification. To verify the accuracy of the numerical program, the simulation results were compared with the analytical solutions of the classical models of Hunt and Shercliff.\(^{14,15}\) The channel model is a rectangle of 20 × 20 × 50 mm, with the boundary conditions consistent with those in the literature.\(^{14,15}\) The Hunt model has two conductive walls and two insulating walls, while the Shercliff model has all walls as insulating walls. The ratio of the inner velocity to the inlet velocity is defined as the jet ratio. The simulation results of the jet ratios are in good agreement with Hunt and Shercliff analytical solutions, respectively, as depicted in Figures 2 and 3.

3.2. Impacts of External Magnetic Intensity on the Flow Field in the Power Generation Channel. Figure 4 indicates that magnetic intensity has a large impact on the

![Figure 2. Comparison of the simulation results with Hunt analytical solutions.](image1)

![Figure 3. Comparison of the simulation results with Shercliff analytical solutions.](image2)

![Figure 4. Turbulence intensity distribution at y = 0.01 under different magnetic intensities: (a) B = 1 T; (b) B = 2 T; (c) B = 3 T.](image3)
turbulence intensity distribution. With the increase in magnetic intensity, the turbulence intensity increases gradually, and the jet-flow effect becomes more significant (Figure 5). Besides, as the external magnetic intensity rises from 1 T to 3 T, the flow velocity in the center of the flow field drops from 3 to 0.5 m/s, implying that the flow state inside the channel changes dramatically.

The applied magnetic intensity affects the flow field via the Lorentz Force. This force on the liquid metal inside the power generation channel increases with the magnetic intensity, which results in a decrease in the velocity at the center of the flow field and a corresponding increase in jet-flow velocity on both sides. This non-uniform velocity distribution increases the turbulence intensity. Therefore, increasing the magnetic strength will reduce the flow. In the system design, the output power cannot be improved by blindly increasing the magnetic intensity.

3.3. Impacts of the Void Fraction on the Flow Field in the Power Generation Channel. Figures 6 and 7 show the turbulence intensity and velocity distributions under different void fractions, respectively. It can be seen from the figures that with the rise of void fraction, the turbulence intensity inside the channel gradually reduces, as well as the jet-flow effect. The turbulence intensity distribution is consistent with the velocity distribution, and the more uniform the velocity distribution, the less the turbulence intensity.

The void fraction of the gas–liquid two-phase flow in the power generation channel affects the flow field in that with the increase of void fraction, the overall electric conductivity of two-phase flow decreases, as well as the Lorentz force on the fluid. With the decrease of the Lorentz force, its influence on the flow velocity declines, which weakens the jet-flow effect and turbulence intensity of the flow field.

3.4. Impacts of the Bubble Diameter and Slip Velocity on the Flow Field in the Power Generation Channel. The bubble diameter has a marginal impact on the turbulence intensity distribution, as presented in Figure 8. The M-shape distribution becomes more cuspatate when the bubble diameter grows from $1 \times 10^{-5}$ to $50 \times 10^{-5}$ m. Since the size of the bubble diameter does not affect the Lorentz force, it has
almost no impact on the overall velocity distribution; however, the bubble diameter has an impact on the two-phase slip velocity, increasing the bubble diameter will reduce the viscous force of the two phases, resulting in an increase of gas–liquid slip velocity and slip loss, which may affect the turbulence intensity.

In order to further observe the effect of slip velocity on the flow field, a physical model with a width to height ratio of 4 was selected, which is a \((80 \, \text{mm}) \times b \times c \approx (200 \, \text{mm})\). By observing the spatiotemporal evolution of the gaseous phase in the channel, the influence of slip velocity on the flow field is studied. It can be noticed from Figure 9 that at \(0.02 \, \text{s}\), the slip velocity first appears on the wall sides. Due to a higher viscosity of liquid metal than that of the gas phase, the velocity of liquid metal on the wall will be less than that of the gas, causing the liquid to squeeze the gas off the wall. At \(0.10 \, \text{s}\), the void fraction in the central region decreases. The Lorentz force reduces the liquid velocity, pushing the gas phase sideways. At \(0.48 \, \text{s}\), the flow reaches a relatively stable status, with the void fraction distribution exhibiting an M-shape. Due to the combined effects of viscous force on the wall and Lorentz Force on the liquid metal, the gas phase is forced to both sides, which leads to a less void fraction in the central and wall regions and a higher void fraction between the two regions. Figure 10 depicts the velocity streamlines on the cross section \(x = 0.05\) at \(t = 1 \, \text{s}\) when the electric current and voltage in the channel reach stable. In addition to the forward flow, the two-phase flow has the transverse velocity as well, which is caused by the applied magnetic field. The fluid in the center flows to both sides, while the fluid near the wall moves in the opposite direction, resulting in a jet-flow effect. In general, the
gas–liquid two-phase flow in the power generation channel will be separated due to the slippage in the magnetic field, which results in a non-uniform conductivity distribution and changes the current density distribution in the flow field. The uneven conductivity will lead to more eddy currents and reduce the power generation efficiency.

4. CONCLUSIONS
In this paper, a numerical investigation is carried out on the gas–liquid two-phase flow in the MHD power generation channel. The effects of applied magnetic intensity, void fraction, bubble diameter, and slip velocity on the internal flow field are discussed in detail, with the main conclusions as follows.

1) The simulation results of the jet ratios are in good agreement with Hunt’s and Shercillif’s analytical solutions, which indicates that the present numerical model and program have a high accuracy dealing with the gas–liquid two-phase flow in the MHD power generation channel.

2) The turbulence intensity and jet-flow effect in the channel increase with the increase of magnetic intensity. In the practical application of the power generation channel, an appropriate external magnetic field intensity should be selected to obtain higher output power and more stable flow field.

3) The turbulence intensity and jet-flow effect decrease with the increasing void fraction. However, the increasing void fraction will result in a decrease in the fluid’s conductivity.

4) The gas–liquid slip velocity changes over time as the power generation channel begins to work, and eventually reaches a stable state and maintains a dynamic equilibrium. Due to the slip velocity under the combined effects of viscous force and Lorentz force, the gas phase is forced sideways, leading to a less void fraction in the central and wall regions and a higher void fraction between them.

■ AUTHOR INFORMATION

Corresponding Authors
Peng Lu — Jiangsu Province Key Laboratory of Aerospace Power System, Key Laboratory of Thermal Environment and Structure of Ministry of Industry and Information, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China; Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, Southeast University, Nanjing 210096, China; orcid.org/0000-0002-0938-1351;
Email: plu@nuaa.edu.cn

Hulin Huang — College of Astronautics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China;
Email: hlhuang@nuaa.edu.cn

Authors
Riliang Fang — College of Astronautics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
Qiang Ye — Jiangsu Province Key Laboratory of Aerospace Power System, Key Laboratory of Thermal Environment and Structure of Ministry of Industry and Information, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c04379

Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work is supported by the “National Key R&D Program of China” (no. 2019YFB1901302); “National Natural Science Foundation of China” (no. 51876090), “Equipment Advance Research Project” (no. JZXSY20190221000301), and “the Fundamental Research Funds for the Central Universities” (no. NT2019006).

■ NOMENCLATURE

B=strength of the magnetic field, T
a=width of power generation channel, mm
b=height of power generation channel, mm
c=length of power generation channel, mm
d=bubble diameter, m
R_L=load resistance, Ω
t=time, s
V=velocity, m·s⁻¹
\( \dot{V}_f \)=velocity of gas, m·s⁻¹
\( \dot{V}_l \)=velocity of liquid, m·s⁻¹
P=pressure, Pa
T=temperature, K
T_g=temperature of gas, K
T_l=temperature of liquid, K
Q=sum of the work done by the viscous term, heat conduction energy, and Joule heat, J
\( \varepsilon \)=total energy, J
\( \varepsilon_g \)=total energy of gas, J
\( \varepsilon_l \)=total energy of liquid, J
\( \Delta \varepsilon \)=momentum of gas–liquid, kg·m·s⁻¹
C_p=energy exchange coefficient
J=current density, A·m⁻²
E=electric field strength, V·m⁻¹
X=axis X, m
Y=axis Y, m
Z=axis Z, m

Greek Symbols
\( \mu_m \)=magnetic conductivity, H·m⁻¹
Φ=potential source term
\( \sigma \)=electrical conductivity, S·m⁻¹
\( \rho_l \)=density of liquid, kg·m⁻³
\( \rho_g \)=density of gas, kg·m⁻³

■ REFERENCES

(1) Koltsakis, N. E.; Kopanos, G. M.; Georgiadis, M. C. Design and operational planning of energy networks based on combined heat and power units. Ind. Eng. Chem. Res. 2014, 53, 16905–16923.
(2) Guo, T. J. Introduction to the research and development of magnetic fluid (MHD) power generation technology. Energy Technol. 1995, 01, 36–39.
(3) Jackson, W. D. Liquid-Metal Faraday-Type MHD Generators. IEEE Trans. Power Appar. Syst. 1962, 82, 904–907.
(4) Dunn, P. F.; Fabris, G.; Pierson, E. S.; Petrick, M. Two-phase liquid-metal MHD generator experiments and pressure-gradient correlations. Argonne National Laboratory; 1980.
(5) Liao, M.; Dai, C. H.; Ma, C.; Liu, Y.; Zhao, Z. J.; Liu, Z. Y.; Asme, NUMERICAL STUDY ON THE TWO-PHASE FLOW FOR A GAS/LIQUID METAL MAGNETOHYDRODYNAMIC GEN-
ERATOR. In the 26th International Conference on Nuclear Engineering, ASME: 2018.

(6) Saito, M.; Inoue, S.; Fujii-E, Y. Gas-Liquid Slip Ratio and MHD Pressure Drop in Two-Phase Liquid Metal Flow in Strong Magnetic Field. *J. Nucl. Sci. Technol.* 1978, 15, 476–489.

(7) Fabris, G. Formulation of the Slip Loss in a Two-Phase Liquid-Metal Magneto-hydrodynamic Generator. *Am. Inst. Aeronaut. Astronaut.* 1981, 216–224.

(8) Fabris, G.; Hantman, R. G. Interaction of fluid dynamics phenomena and generator efficiency in two-phase liquid-metal gas magnetohydrodynamic power generators. *Energy Convers. Manage.* 1981, 21, 49–60.

(9) Fabris, G.; Pierson, E. S. The role of interfacial heat and mechanical energy transfers in a liquid-metal MHD generator. *Energy Convers. Manage.* 1979, 19, 111–118.

(10) Fabris, G.; Kwack, E.; Harstad, K.; Back, L. H. Two-phase flow bubbly mixing for liquid metal magnetohydrodynamic energy conversion. In *25th Intersociety Energy Conversion Engineering Conference*, American Institute of Chemical Engineers 1990; pp. 486–493.

(11) Yamaguchi, H.; Niu, X. D.; Zhang, X. R. Investigation on a low-melting-point gallium alloy MHD power generator. *Int. J. Energy Res.* 2011, 35, 209–220.

(12) Kobayashi, H.; Shionoya, H.; Okuno, Y. Turbulent duct flows in a liquid metal magnetohydrodynamic power generator. *J. Fluid Mech.* 2012, 713, 243–270.

(13) Huang, Z. Y.; Liu, Y. J.; Wang, Z. Y.; Cai, J. Three-dimensional simulations of MHD generator coupling with outer resistance circuit. *Simul. Model Pract. Theory* 2015, 54, 1–18.

(14) Hunt, R. J. C. Magnetohydrodynamic flow in rectangular ducts. *J. Fluid Mech.* 1965, 21, 577–590.

(15) Shercliff, J. A. Steady motion of conducting fluids in pipes under transverse magnetic fields. *Math. Proc. Cambridge Philos. Soc.* 1953, 49, 136–144.