IMPACT OF ELECTRICAL AND MAGNETIC FIELD ON COOLING PROCESS OF LIQUID METAL DUCT MAGNETOHYDRODYNAMIC FLOW

by

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Cooling period of liquid metal while flowing under imposed magnetic and electrical field was studied for laminar steady flow condition. Computational analyses were done by ANSYS Fluent software MHD module. For applied each constant value of magnetic field induction ($B = 0$ T, $B = 0.05$ T, $B = 1$ T), the electrical field intensity was applied positively as E_+ (1e-4, 1e-5) V/m and negatively as E_-(–1e-4, –1e-5) V/m. Increase of the E+ field intensity decreased the local temperature (increased cooling rate) but also increased the heat flux and Nusselt number. Also, decrease of E_- in the opposite direction increased the temperature but also decreased the heat flux and Nusselt number. It could be signified that by the application of magnetic field or together with electrical field, the heat transfer could be improved or attenuated.

Key words: *magnetohydrodynamic, magnetic field, electrical field, convectional heat transfer, Nusselt number*

Introduction

It is known that hydrodynamic behaviours of electrically conductive fluids could be controllable by the magnetic effects. This study cares about the magnetic effects on thermal behaviours of the fluids. Chinyoka *et al.* [1] examined the convective cooling of MHD flow and heat transfer characteristics. Magnetic forces result in increased resistance to flow and thus explain the reduction in fluid velocity with increasing Hartmann number. The reduced velocity in turn decreases the viscous heating source terms in the temperature equation and hence correspondingly decreases the fluid temperature. Heidary *et al.* [2] studied numerically heat transfer and nanofluid flow analysis in a straight channel, while flow field is under magnetic field. It is concluded that heat transfer in channels can be enhanced up to about 75% due to the presence of magnetic field. Fakour *et al.* [3] investigated laminar fluid flow and heat transfer in channel with permeable walls in the presence of a transverse magnetic field. It is concluded that by applied magnetic field, velocity in the channel is reduced and the maximum amount of temperature increases. Selimli *et al.* [4] studied computationally combined effect of externally applied magnetics and electrical field on the magneto-viscous fluid-flow. It is concluded that increase of positive directional electrical and magnetic field decreases the flow velocity. However, shear stress, temperature, surface heat flux and Nusselt number is boosted by

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the increase of positive directional electrical and magnetic field. Negative directional electrical field weaken the impact of magnetic field. Khan *et al.* [5] studied steady flow of an electrically conducting, viscous incompressible nanofluid past a continuously moving surface in the presence of uniform transverse magnetic field. The results revealed that heat transfer rate increases by the increase of magnetic parameter. Cao *et al.* [6] studied the numerical simulation of laminar flow regime at constant heat flux boundary condition with water. The near wall region has larger velocity and velocity gradient, accounting for the heat transfer enhancement mechanism. Sahin *et al.* [7] carried out a numerical study about unsteady heat and mass transfer by free convection flow of a viscous, incompressible, electrically conducting Newtonian fluid. It is found that velocity is reduced considerably with a rise in the magnetic body parameter, whereas the temperature and concentration are found to be markedly boosted with an increase in the magnetic body parameter. Vidyasagar *et al.* [8] studied convective heat and mass transfer in a porous medium of an incompressible viscous conducting fluid. It is noticed that the temperature and concentration increases with the increase of magnetic parameter. Mansour *et al.* [9] studied the effects of magnetic force, acting vertically downward on natural convection within a nanofluid filled tilted trapezoidal enclosure saturated with an electrically conducting fluid. As a result, Hartmann number increases the temperature gradients increases, hence heat transfer rate increases Jat and Chand [10] studied the steady 2-D laminar flow of a viscous incompressible electrically conducting fluid. Results showed that the shear stress decreases and heat transfer rate increases as magnetic parameter increases. Alammar *et al.* [11] simulated the fully-developed average turbulent MHD pipe flow with wall heating. Effect of Reynolds, Hartmann, and Prandtl numbers on heat transfer characteristics was investigated. With increasing Hartmann number, heat transfer was shown to increase towards the side layer. Ashraf and Rashid [12] numerically analysed MHD 2-D boundary-layer stagnation point flow with radiation and heat generation characteristics towards a heated shrinking sheet immersed in an electrically conducting incompressible micropolar fluid in the presence of a transverse magnetic field. Results showed that the heat transfer rate from the sheet to the fluid boundary-layer thickness increases by increasing the increases for strong applied magnetic field. Recebli *et al.* [13] studied the effect of perpendicularly applied magnetic field on steady-state laminar liquid lithium flow in a horizontal circular pipe. During the heating of liquid lithium Nusselt number was increased by the increase of magnetic field induction. Nyabuto *et al.* [14] studied the steady MHD stokes free convection flow of an incompressible, electrically conducting fluid between two parallel infinite plates. The results that, increase in Hartmann number is found to cause a decrease in velocity profiles and an increase in temperature distribution. Uddin *et al.* [15] studied the 2-D steady forced convective flow of a Newtonian fluid. The rate of heat transfer elevates with mass transfer velocity, convective heat transfer, Prandtl number, velocity ratio, and magnetic field parameters. Rushikumar and Gangadhar [16] analysed the influence of the heat and mass transfer characteristics of a 2-D steady laminar free convective flow of a viscous incompressible fluid between two parallel porous walls. The temperature component, θ, increases with an increase of magnetic field parameter. Chamka and Ahmed [17] focused on MHD heat and mass transfer by mixed convection flow in the forward stagnation region of a rotating sphere. Increasing the value of the magnetic field parameter resulted in increases in both of the local coefficients of surface shear stresses, temperature, and solute concentration in the fluid. Aydin and Kaya [18] studied the problem of steady laminar MHD mixed convection heat transfer. It is determined that the local skin friction coefficient and the local heat transfer coefficient increase. Ishak *et al.* [19] investigated the steady 2-D stagnation point flow of an incompressible viscous and electrically conducting fluid, subject to a transverse uniform magnetic field. It is found that the heat transfer rate at the surface increases with the magnetic parameter. Mohebujjaman *et al.* [20] considered the steady 2-D MHD heat transfer mixed convection flow of a viscous incompressible fluid. Study clearly showed that velocity decreases but the temperature increases as we increase the magnetic field parameter. Makinde [21] studied the hydromagnetic boundary-layer flow with heat and mass transfer over a vertical plate in the presence of magnetic field. It was found that the local heat and mass transfer rate at the plate surface increases with an increase in intensity of magnetic field. Recebli *et al.* [22] numerically studied the effect of magnetic field on heat convection with finite element method. The study also indicated that increasing the effect of magnetic field increases Nusselt number. Rahman *et al.* [23] analysed the MHD natural convection flow of an electrically conducting fluid along a vertical flat plate. The temperature within the boundary-layer increases for the increasing magnetic parameter. Abbasi and Nassrallah [24] investigated the laminar flow of a viscous incompressible electrically conducting fluid. Heat transfer is significantly enhanced by the magnetic field in the case of fluids of high Prandtl numbers. Cooling of liquid metal in a rectangular conduit with constant wall temperature was studied during the magnetics and electrical field was perpendicularly applying on flow stream. Evaluations were occurred in the sense of the heat transfer.

Material and methods

Laminar, steady-state liquid metal rectangular duct flow while applying magnetic and electrical field has been analysed by MHD base software. The model constructed with two narrow electrically conductive and two wide electrically insulated walls. The model was given in fig. 1.

The positive (+) and negative (–) electrical potentials were applied on the conducting walls. Magnetic field applied through the $-y$-direction on to the duct model. Fluid flow occurred in the $+x$-direction. Magnetic and electrical fields are applied perpendicularly to each other and also applied normally on to flow stream lines. The boundary conditions were taken as $T_w = 473.15$ K, $T_{in} = 573.15$ K, and $U_i = 0.28$ m/s. The laminar flow condition was provided by Re = 2267, thermal and hydraulic entry lengths was specified by eqs. (1) and (2) to specify the hydraulic and thermal behaviour of the flow:

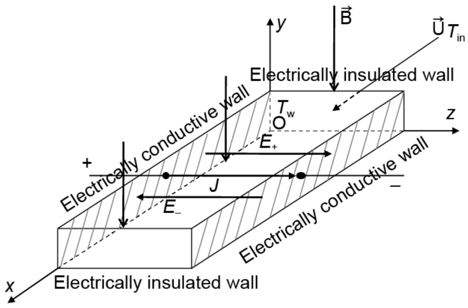

Figure 1. Duct model

$$L_{h,\,laminar} = 0.05 \,\mathrm{Re}\, D_h \tag{1}$$

$$L_{t,\,laminar} = 0.05 \,\mathrm{Re}\, D_h \,\mathrm{Pr} \tag{2}$$

Hydraulic and thermal length were $L_h = 0.9$ m and $L_t = 0.06$ m. Investigation of flow and thermal characteristic was done at the $L = 0.12$ m thermal fully developed flow region. General MHD differential equations are given in vectorial form as seen in eqs. (3)-(6).

Momentum (Navier-Stokes equation):

$$\rho\left[(U\nabla)U\right] = -\nabla P + \mu\Delta U + J \times B \tag{3}$$

– Ohm law equation:

$$J = \sigma(E + U \times B) \tag{4}$$

– continuity equation:

$$\mathrm{div}U = 0 \tag{5}$$

– energy equation:

$$\rho c_p \left[(U\nabla)T \right] = k\Delta T + \phi \tag{6}$$

Analyses were occurred by ANSYS Fluent software MHD module due to the given equations as seen in eqs. (3)-(6). The model was generated and meshed with Gambit software in 0.0002, 0.00025, 0.0003, 0.0004, and 0.0005 m sizes. Optimum mesh size is important to obtain accurate results by numerical analyses. Liquid metal physical properties were taken from the NASA and ORNL Report that are given in [25, 26] as the temperature dependent empirical relation. These relations were used to write user defined function to the determination of user defined material in ANSYS Fluent. In this respect, the mesh study was done by ANSYS Fluent software without magnetic field. Local velocity profiles at 0.12 m of duct were compared to each other. Local velocity profiles comparison was given in fig. 2.

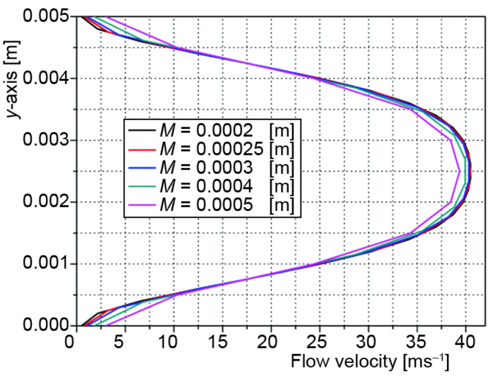

Figure 2. Comparison of local velocities for mesh study (*for color image see journal web site*)

Figure 2 represents that, the velocity values converged each other for the 0.0002 m and 0.00025 m mesh sizes. So, to obtain smooth surface transition of profiles and minimum time consumption while analyzing, the examination mesh size was chosen as 0.00025 m. Magnetic field induction and electrical field intensity values are assumed as B = 0 T, B = 0.05 T, B = 1 T, and ±1e–4 V/m, ±1e–5 V/m for the computational analyses.

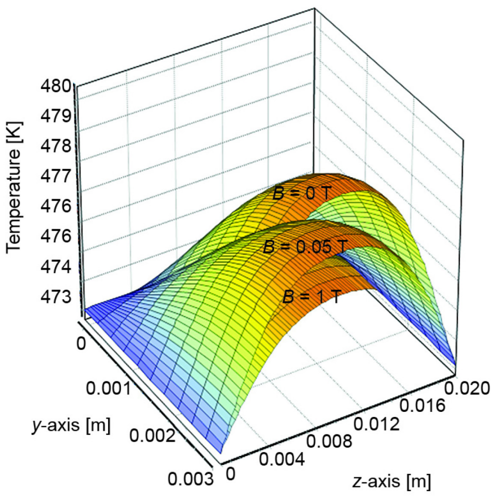

Figure 3. Temperature profile at z = 0.12 m (*for color image see journal web site*)

Results and discussion

Thermophysical behaviour of the internal steady-state MHD liquid metal flow in a rectangular duct was examined. Local temperature profile at 0.12 m of the duct under the applied magnetic field was examined. For each constant value of magnetic field induction are B = 0 T, B = 0.05 T, B = 1 T, the local temperature was shown in fig. 3 for the cooling of liquid metal with constant wall temperature.

Figure 3 shows that increase of magnetic field induction, the temperature value was decreased. While applying B = 0.05 T and B = 1 T the decrease rate is 0.38% and 0.68% according to the B = 0 T. Similar effect of magnetic forces on the flow body temperature was clarified in [3, 5, 7, 8] as temperature increases with increase in the magnetic field intensity parameter. Temperature profile at thermally fully developed region (0.12 m of the length) was represented in fig. 4 for constant value of magnetic induction value is B = 0.05 T and the electrical field intensity applied as $E_{\pm}$ = 1e–4 V/m.

Figure 4 clarifies the variation of local temperature under the applied constant magnetic field B = 0.05 T and electrical field intensity value are E_+ = 1e–4 and E_- = −1e–4 V/m. While magnetic field was applied as B = 0.05 T, the local temperature was decreased for applied electrical field intensity is E_+ = 1e–4 V/m. The temperature increased in case of application of E_- = −1e–4 V/m. The decrease and increase rates are 0.64% and 0.8% during the cooling of liquid metal. Temperature profile at thermally fully developed region (0.12 m of the length) was represented in fig. 5 for constant value of magnetic induction value is B = 1 T, and the electrical field intensity is $E\pm$ = 1e–4 V/m.

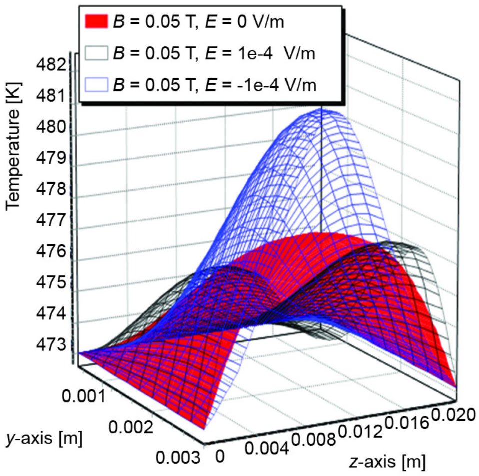

Figure 4. Local temperature profile at z = 0.12 m for B = 0.05 T
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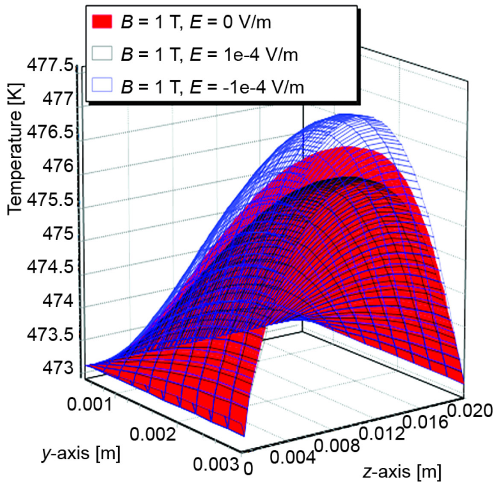


Figure 5. Local temperature profile at z = 0.12 m for B = 1 T
(*for color image see journal web site*)

Figure 5 presents the variation of local temperature under the influence of applied constant magnetic field B = 1 T and electrical field intensity value are E_+ = 1e–4 and E_- = −1e–4 V/m. While magnetic field is constantly applying on the flow domain with the value is B = 1 T, the local temperature was decreased by the influence of electrical field intensity is E_+ = 1e–4 V/m. The temperature increased by application of E_- = −1e–4 V/m. The decrease and increase rates are 0.1% and 0.1%. Figure 6 shows the effect of magnetic forces on surface average values of heat flux from liquid metal to cold boundary walls of the model.

As seen in fig. 6 designates that applied electrical field do not have any effect on heat flux without magnetic field. Increase in positive directionally applied electrical field with magnetic field enhanced the heat flux from the flow domain. However, it is seen that negative directionally applied electrical field with magnetic field behaves reverse effect and so reduces the heat flux from the flow body. In [4, 6, 12, 18] is clearly seen that increase of positive directional electrical and magnetic field increases surface heat flux but also Negative directional electrical field weaken the impact of magnetic field. The variation of volume average rate Nusselt number was evaluated by the application of electrical field intensity values are as

±1e–4 V/m, 0 V/m, ±1e–5 V/m during the application of magnetic field induction (B = 0 T, B = 0.05 T, and B = 1 T) and was presented in fig. 7.

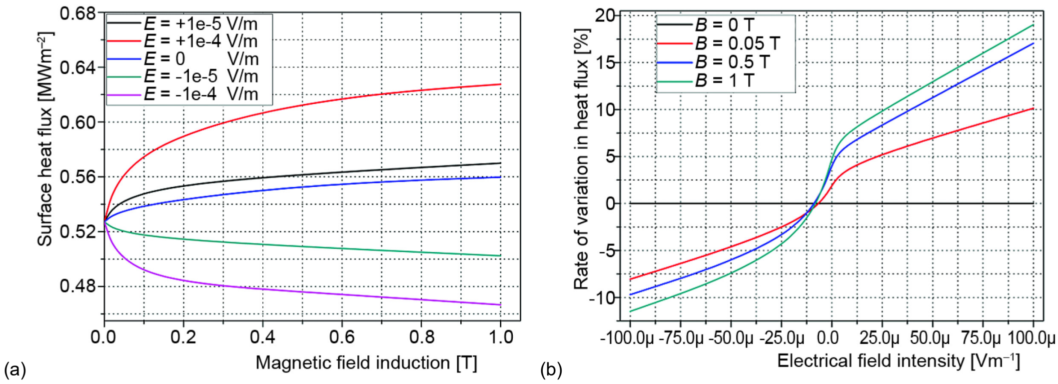


Figure 6. Variation of the (a) heat flux and (b) rate of change in it

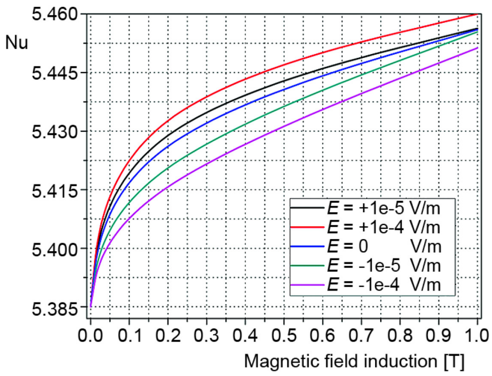
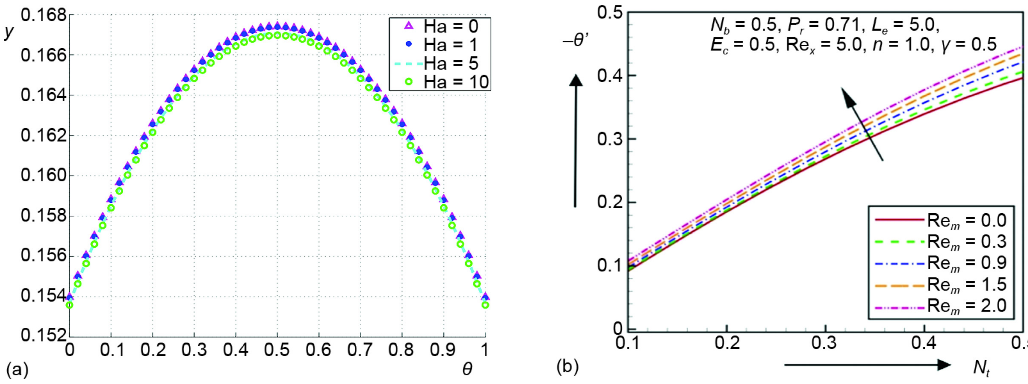


Figure 7. Variation of volume average of Nusselt number

Figure 7 shows that, increase of magnetic field induction, increased the Nusselt number and so enhanced the heat transfer rate. Also, increase of E_{+} from 0 to 1e–4 increased the Nusselt number, but also decrease of E_{-} from 0 to –1e–4 decreased the Nusselt number. Variation of Nusselt number and so heat transfer was determined in [2, 9-11] as heat transfer in channels can be enhanced up to about 75% due to the presence of magnetic field.

Evaluated results could be supported by the similar studies from the literature. Some of the graphs that are taken from the current ones are given in figs. 8(a)-8(c) that illustrates the effect of magnetic forces on the parameters are dimensionless temperature, heat transfer rate, and Nusselt number.

Figures 8(a)-8(c) designate that increase in magnetic parameter decreases the flow temperature as discussed in [1] decrease in velocity in turn decreases the viscous heating source terms in the temperature equation and hence correspondingly decreases the fluid temperature. Increase in magnetic parameter, increases the heat transfer rate discussed in [5] that heat transfer rate increases by the increase of magnetic parameter. Increase in magnetic parameter increases, the average Nusselt number enhance, since as magnetic field is applied, the Lorentz force at the middle section of the channel, decreases the velocity at the centre side of the channel in [2] similar effect is observed in this study.



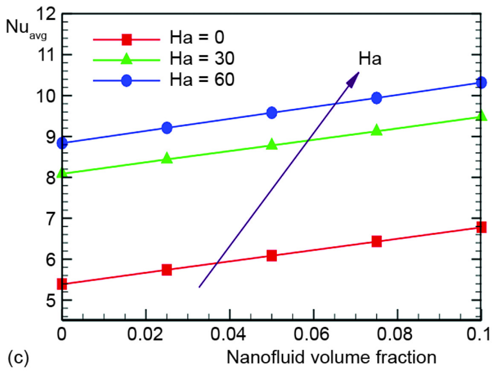


Figure 8. (a) Temperature distribution for various values of magnetic parameter [1], (b) effects of magnetic parameter on heat transfer rate [5], (c) average Nusselt number *vs.* nanofluid volume fraction for various Hartman number [2]
(*for color image see journal web site*)

Conclusion

The thermophysical characteristic of steady-state laminar liquid metal flow was studied. It is concluded that for applied each constant value of magnetic field induction, the electrical field intensity was increased from $E_+ = 0$ to 1e–4 and decreased in the opposite direction from $E_- = 0$ to −1e–4 V/m. As a result, increase of E_+ intensity decreased the temperature (increased cooling rate) but also increased heat flux and Nusselt number for each constant value of magnetic field induction. Temperature was increased (decreased cooling rate) but also heat flux and Nusselt number was decreased in case of the changes of the electrical field direction and by the decrease of E_-. Consequently, increase of the magnetic and electrical field enhanced the cooling process heat transfer rate was enhanced.

Nomenclature

B – magnetic field induction, [T]
c_p – specific heat, [Jkg^{-1}K^{-1}]
D_h – hydraulic diameter, [m]
E – electrical field intensity, [Vm^{-1}]
Ec – Eckert number
E_+ – applied electrical field intensity which is in same direction with (= $U \times B$) vectorial multiplication, [Vm^{-1}]
E_- – applied electrical field intensity which is in opposite direction with (= $U \times B$) vectorial multiplication, [Vm^{-1}]
Ha – Hartmann number
J – current density, [Am^{-2}]
k – thermal conductivity of the fluid, [Wm^{-1}K^{-1}]
L – length, [m]
Le – Lewis number
L_h – hydraulic entrance length, [m]
L_t – thermal entrance length, [m]
N_b – Brownian motion parameter
N_t – thermoforesis parameter
Nu – Nusselt number
n – exponent parameter
P – pressure, [Pa]
Pr – Prandtl number
Re – Reynolds number
$\mathrm{Re_m}$ – magnetic parameter

Re_x – local Reynolds number
T – temperature, [K]
T_w – wall temperature, [K]
T_i – İnlet temperature, [K]
U – velocity, [ms^{-1}]
U_i – inlet velocity, [ms^{-1}]
∇ – del operator in Cartesian co-ordinates ($= i\,\partial/\partial x + j\,k\,\partial/\partial y + k\,\partial/\partial z$)
Δ, ∇^2 – Laplace operator in Cartesian co-ordinates ($= \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$)
$\vec{x}, \vec{y}, \vec{z}$ – unit vectors in Cartesian co-ordinates

Greek symbols

μ – dynamic viscosity, [Pa·s]
ρ – density, [kgm^{-3}]
σ – electric conductivity, [Sm^{-1}]
ϕ – viscous dissipation function [–]
γ – chemical reaction parameter
θ – dimensionless temperature parameter, fig 8(a); reduced Nusselt number, fig. 8(b)

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