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Effects of chemically reactive and thermally radiative MHD Prandtl nanofluid by a vertically heated stretchable surface with convective conditions

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Abstract: The existing investigations purpose to disclose the interaction effects of transverse magnetic and hydrodynamic flow of Prandtl nanofluid subjected to convective boundary conditions over a vertical heated stretching surface. Developing a fundamental flow model, a boundary layer approximation is done, which yields momentum, concentration, and energy expressions. Moreover, Brownian effect and thermophoresis influence are also taken into the account. The constitutive flow laws of nonlinear (PDEs) is altered into ordinary one via similarity transformation variables. The dimensionless nonlinear systems of (ODEs) are then solved through bvp4c numerical algorithm. Consequences of innumerable flow factors on steam wise velocity, thermal field, and concentration of nanoparticle are explicitly debated and plotted graphically. The drag force coefficient and heat transference rate are assumed and deliberated accordingly. It has been perceived that f higher estimation of thermophoresis parameter upsurges the internal thermal energy of the nanofluid and nanoparticles concentration field.

Keywords: Numerical solution, Chemical reaction, Brownian motion, Thermophoresis, MHD flow, Prandtl nanofluid

1. Introduction

Almost all fluids that occur in the process of radiation and chemical reactions unable to comply with classical Newton’s law which categorized as non-Newtonian fluids. Due to the majority of applications of these fluids in different fields like technology, petroleum production, biochemical, pharmaceutical, food, and power engineering, considerable attention has been given by researchers and scientists to study the physical aspects of such fluids. Besides this, because of the budding utility of non-Newtonian fluids in large numbers of industrial and manufacturing practices, more attention paid to the analysis of heat transfer features of these fluids. However, a practical approach was taken into consideration, the various systems have been suggested to analyze the structural behavior of these fluids namely the Power-law model, Carreau model, the Rivlin-Ericksen model, Williamson model, Powell-Eyring model, Prandtl model, Ellis model. These models are basically characterized into viscoelastic and inelastic fluids, micro-structure fluids, and polar fluids. Among these, the visco inelastic fluids are important in the view of the mixed effects of elastic and viscous characteristics. Akbar et al. [1] analyzed the result of magnetized Prandtl flow driven by stretching sheet through the porous plate. Bilal et al. [2] studied the impact of double diffusion on Prandtl nanofluid considering stretched sheet under magnetic effects. Nadeem et al. [3] analyzed the peristaltic movement of a Prandtl fluid model analytically. Khan et al. [4] investigated heterogeneous and homogeneous reactions over Prandtl fluid at the stretched sheet. Further, Amanullah et al. [5] studied the Prandtl-Eyring fluid flow over an isothermal sphere under magnetic strength and permeable medium. Mukhopadhyay [6] showed the slip effects of
magnetized flow past an exponential stretched sheet under radiative flux. Ali et al. [7] elaborated the unsteady Powell-Eyring nanofluid over a stretching sheet. The massive information on visco-inelastic model examined by many authors has been listed in [8-16]. Several examinations have been carried out by the researchers to enhance the thermo-physical characteristics in conventional heat transfer fluids. Unfortunately, the expectation of modern technology could not have satisfied by these fluids. Because most of the fluids like glycol, water, oil, and many more are low conductors of heat due to the poor thermal conductivity. Hence, to cope up with this situation, nanoparticles are introduced in the fluids. Nanofluids are developed by immersing tiny particles in the base fluid. Because of nanofluids, a reduction in thermal resistances is observed as they can easily flow through the microchannels benefited by their extra small size (10-50 nm). Choi [17] coined the phenomena of the “Nanofluid”. He proved that the inclusion of the nanoparticles in the liquid causes to rise in thermal conductivity tremendously. Chiller, microelectronics, fuel cells, hybrid power industries are witnesses of such processes. Reddy and Sreedevi [18] presented the influence of chemical reaction on heat and mass transfer features of nanofluid past stretched sheet through porous media. Abbas et al. [19] analyzed the Darcy Forchheimer nanofluid flow under magnetism subject to stretching surface. Gireesha et al. [20] discussed the MHD stagnation flow consisting of magnetized nanofluid against a stretched surface. Sreedevi and Reddy [21] discussed the characteristics of thermophoresis and Brownian motion over the three-dimensional Maxwell nanofluid flow due to stretching sheet considering radiation and chemical reaction. Recently, various excellent investigations on vital features of nanofluid were reported by [22-28]. MHD flows in association with a stretching sheet have immense implications in technical and modern industrial practices such as hot rolling, glass fiber, cooling in nuclear reactors, plastic sheets extrusion, metal casting, glass blowing, and metallurgical casting. Magnetized nanofluid flow passed a perpendicular permeable surface was shown by Das et al. [29]. Ibrahim et al. [30] elaborated the power of chemical reaction on the mixed convective flow of Casson nanofluid over a stretched surface under magnetic strength effect. Kumar et al. [31] studied micro-polar fluid flow with magnetism and radiation at a stretching surface. Aziz and Afify [32] reported the Casson MHD flow driven by stretched sheet through slip velocity and claimed that for magnetic parameter less than one, heat transfer rate enhanced and vice versa. The study of heat transfer associated with radiation has gained considerable attention by the researchers because of vast utility in the technological applications which includes missiles, space technology, nuclear power plant, gas turbines. Mabood and Das [33] discussed the MHD viscoelastic fluid of Casson liquid in a porous regime under the radiation effects. Dogonchi and Ganji [34] analyzed MHD nanofluid flow past parallel plates caused by the radiation. Gupta et al. [35] presented Brownian movement and Thermophoresis effects on the nanofluid over inclined stretched sheet under chemical and radiative flux. Sheikhoslami and Shamlooie [36] explored natural convection flow of nanofluid under magnetism and radiation. Alkanhal [37] showed the thermal impact on MHD nanofluid flow over permeable surface under radiative heat sources and magnetic strengths.

2. Framework of the flow problem

Here, we have assumed two-dimensional unsteady viscoelastic incompressible boundary layer flow of non-Newtonian Prandtl nanofluid in view of vertically heated stretchable surface along with thermal radiation is considered in modeling for the flow problem the formulation formulated.
The fluid motion with stretching sheet is taken onwards the \( x - \text{axis} \) and \( y - \text{axis} \) is horizontal to it.

Physical configuration and Coordinate system is shown in Fig. 1. The flow under consideration is sketched below.

**Fig.1** Physical sketched of flow the model.

Here, shear-stress tensor for Prandtl fluid is defined by [38]:

\[
\tau_{xy} = A \sin^{-1} \left( \frac{1}{c_1} \frac{\partial u}{\partial y} \right),
\]

(1)

here, \((A)\) is fluid consistency index and \((c_1)\) material fluid parameter.

the second order approximation of \(\sin^{-1} \left( \frac{1}{c_1} \frac{\partial u}{\partial y} \right)\) by utilizing the Taylor expansion given by the relation

\[
\sin^{-1} \left( \frac{1}{c_1} \frac{\partial u}{\partial y} \right) \approx \frac{1}{c_1} \left( \frac{\partial u}{\partial y} \right) + \frac{1}{6} \left( \frac{1}{c_1} \frac{\partial u}{\partial y} \right)^3, \quad \text{with} \quad \left| \frac{1}{c_1} \frac{\partial u}{\partial y} \right| \leq 1,
\]

(2)

Then the governing model becomes,

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0,
\]

(3)
The particular extreme values are:

\[ u = U_w(x,t), \quad v = 0, \quad -k \frac{\partial T}{\partial y} = (T_w - T)h(t), \quad C_w = C \text{ for } y = 0 \]

and \[ u = U_e(x,t), \quad T \to T_w, \quad C \to C_w \text{ for } y \to \infty \]

The radiation heat flux \( q_r \) [16] mathematically expressed as:

\[ q_r = -\frac{4\sigma^*}{3K^*} \frac{\partial T^4}{\partial y} \]

In heat flux relation \( \sigma^* \) denote Stefan-Boltzman constant, \( K^* \) coefficient of absorption. Temperature variation within the flow field is considered in such a way that the nonlinear term \( (T^4) \) appearing in the above equation can be linearize using the Taylor’s series expansion about \( (T_w) \) and omitting high power terms we obtain, \( T^4 \approx 4T_w^3T - 3T_w^4 \).

Following are the similarity transformations,

\[ \eta = \frac{a}{\sqrt{v(1-ct)}}, \quad \nu = -\frac{va}{\sqrt{1-ct}}f'(\eta), \quad u = \frac{ax}{1-ct}f'(\eta), \quad \theta(\eta) = \frac{T-T_w}{T_w-T_x}, \]

\[ \phi(\eta) = \frac{C-C_w}{C_w-C_x}, \quad h(\eta) = \frac{d}{1-ct}, \quad u_e = \frac{bx}{1-ct}, \quad U_w = \frac{ax}{1-ct} \]

In view of similarity transformation, the governing equations (3)-(7), reduced to dimensionless form by

\[ \varepsilon \left[ 1+\delta(f^2)^2 \right] f'' + \lambda \left( \frac{\eta}{2} f'' + f' \right) + ff'' - \left( f' \right)^2 + (B\lambda + B_x^2) - Mf' = 0, \]

\[ \frac{1}{Pr} \left( 1+R \right) \theta'' + Nb\phi' + f\theta' + Nt(\theta')^2 - \lambda \frac{\eta}{2} \theta' = 0, \]
\[ \frac{1}{S\epsilon} \left( \phi'' + \frac{Nt}{N\beta} \theta'' \right) + f \phi' + G \phi - \lambda \eta \phi' = 0, \]  

with the transformed boundary conditions,

\[ f(0) = 0, \quad f'(0) = 1, \quad \theta'(0) = -\gamma(1 - \theta(0)), \quad \phi(0) = 1, \quad f'(\infty) = B, \quad \theta(\infty) = 0, \quad \phi(\infty) = 0 \]  

(12)

The pertinent flow parameters appearing in (9)–(12) are defined in (13) by

\[ Nt = \frac{\tau D_T (T_w - T_\infty)}{T_w \nu}, \quad Nb = \frac{\tau D_b (C_w - C_\infty)}{\nu}, \quad Pr = \frac{\nu}{\alpha}, \quad Sc = \frac{\nu}{D_b}, \quad \gamma = \frac{d \sqrt{\nu}}{k \sqrt{a}}, \quad \varepsilon = \frac{A}{\mu_c}, \]

\[ \delta = \frac{a^3 \lambda^2}{2 \nu c^2 (1 - \xi)}, \quad \lambda = \frac{c}{a}, \quad B = \frac{b}{a}, \quad R = \frac{16 \sigma^3 T_\infty}{3 k k^2}, \quad G = \frac{K_r (1 - \xi)}{a} \]

(13)

Describes Brownian effect, thermophoresis influence, Prandtl number, Schmidt number, convective parameter/Biot number, fluid parameter, Prandtl fluid factor, unsteady parameter, stretching parameter, radiation parameter and Chemical reaction respectively.

The expressions of physical quantities \((Cf, \quad Nu, \quad Sh)\) are defined by

\[ Cf = \frac{\tau_w}{\rho U_w^2}, \quad Nu = \frac{x q_w}{k (T_w - T_\infty)}, \quad Sh = \frac{x q_m}{D_b (C_w - C_\infty)}, \]

(14)

Here, \(\tau_w\) denote shear stress at the sheet, \(q_w\) heat flux and \(q_m\) mass flux of nanoparticle is written as

\[ \tau_w = A \left( \frac{\partial u}{\partial y} \right)_{y=0} - A \left( \frac{1}{6} \left( \frac{\partial u}{\partial y} \right)^3 \right)_{y=0}, \]

(15)

\[ q_w = -k \left( \frac{\partial T}{\partial y} \right)_{y=0}, \]

(16)

\[ q_m = -D_b \left( \frac{\partial C}{\partial y} \right)_{y=0} \]

(17)

The simplified dimensionless form of (14) for \((Cf, \quad Nu, \quad Sh)\) using (9) we have

\[ (Re_x)^{\frac{1}{2}} Cf = \varepsilon f''(0) - \frac{\varepsilon \delta}{3} f''(0)^3, \]

(18)

\[ (Re_x)^{\frac{1}{2}} Nu = -(1 + R) \theta'(0), \]

(19)
(Re_{x})^{1/2}Sh_{x} = -\phi'(0), \quad (20)

3. Numerical solution

The dimensionless nonlinear system of (ODEs) in (9)–(11) subjected to the associative boundary conditions in (12) are addressed by utilizing Mathematica bvp4c built in numerical algorithm. The following numerical code converts the problem into first order (ODEs).

Let introduce new transformation variables \( w, x, y \) and \( z \) then the system of nonlinear equations (9)–(12) are transformed to first order linear differential equations as,

\[
\begin{align*}
\eta' &= w & (21) \\
\xi' &= x & (22) \\
\phi' &= y & (23) \\
\theta' &= y & (24) \\
\psi' &= \frac{Pr}{(1+R)} \left[ \frac{\lambda}{2} \left( \frac{\eta}{2} x + w \right) - f\xi + w^2 - (B\lambda + B^2) + Mw \right] & (25) \\
\phi' &= z & (26) \\
\psi' &= \left[ Sc \left( \frac{\lambda}{2} \frac{\eta}{2} z - f\xi - G\phi \right) - \frac{Nt}{Nb} \right] & (27)
\end{align*}
\]

with altered conditions,

\[
\begin{align*}
f(0) &= 0, \ w(0) = 1, \ y(0) = -\gamma(1 - \theta(0)), \ \phi(0) = 1, \ w(\infty) = B, \ \theta(0) = 0, \ \phi(\infty) = 0 
\end{align*}
\quad (28)
\]

The process is continued unstill the wanted level of accuracy of \( 10^{-6} \) obtained by taking a mesh size \( \Delta \eta = 0.001 \). The routine bvp4c code/algorithm for numerical solution in Mathematica software is illustrated in Fig. 2.
Fig. 2. Algorithm of bvp4c routine in Mathematica software

4. Result and Discussion

The existing section revelations the consequences of innumerable governing flow factors on velocity, energy and the concentration profile via graphical illustration in Figs. 3–27 of the given problem.

Figure 3 explains the effect of fluid parameter $(\varepsilon)$ on nanofluid velocity gradient $f'(\eta)$. This plot unveils $f'(\eta)$ augmentation for higher $(\varepsilon)$. Here, one can perceive that $f'(\eta)$ enhances when fluid parameter is augmented. In reality, larger $(\varepsilon)$ parameter diminishes fluid viscosity significantly. In consequences, nanofluid velocity augmented. The contribution of fluid parameter $(\varepsilon)$ on thermal field $\theta(\eta)$ is evaluated through Fig. 4. The temperature profile diminishes subject
to higher fluid parameter. Hence, $\theta(\eta)$ decays. Consequence of $\varepsilon$ on concentration field $\phi(\eta)$ is portrayed through Fig. 5. As expected, $\phi(\eta)$ reduces via larger fluid parameter. Hence, energy and concentration profile of the dwindles. Influence of stretching parameter $B$ is interpreted on thermal field $\theta(\eta)$ in Fig. 6. Clearly fluid temperature dwindles subject to larger $B$. Thus, yields a decline in thermal boundary layer. Fig. 7 addresses $B$ effect via $\phi(\eta)$. Larger stretching parameter diminishes the concentration of the nanofluid. Variations in thermal field $\theta(\eta)$ and nanoparticles concentration $\phi(\eta)$ via unsteady parameter $\lambda$ are plotted in Fig. 8 and Fig. 9. Clearly, both thermal field and concentration upsurges for higher estimations of unsteady parameter. Physically, higher unsteady parameter, the internal system becomes more heated due to which the fluid particles have higher kinetic energy releases. In consequences, thermal field increases. Moreover, larger $\lambda$ boosts heat mass transfer rate of the fluid at every point on the surface. The contribution of Brownian motion parameter $Nb$ on thermal and concentration fields are evaluated through Fig. 10. As expected, $\theta(\eta)$ rises. In nanofluids, the Brownian movement rises due to small size nanoparticles and at this point, the fluid particles movement and its influence against fluid has a substantial contribution regarding to the convective heat flow. An increase in $Nb$ yields effective nanoparticles movement inside the nanofluid flow. The strength of this massive movement enhances the nanoparticles kinetic energy. In consequence, fluid temperature upsurges. Fig. 11 explains $Nb$ impact on $\phi(\eta)$. Clearly an upsurge in $Nb$ values escalate the movement through which fluid particles move with diverse direction in arbitrary path owing to Brownian aspect. In consequently, $\phi(\eta)$ decays and related boundary layer thickness subject to higher $Nb$ parameter. Fig. 12 discloses $\theta(\eta)$ variations subject to thermophoresis parameter $Nt$. Here, thermal field upsurges against larger $Nt$. In reality, thermophoretic force upsurges when $Nt$ is augmented. Such force assists to escape nanoparticles by hotter towards colder part and ultimate $\theta(\eta)$ boosts. The contribution of $Nt$ on $\phi(\eta)$ is evaluated through Fig. 13. We witnessed an increment in mass profile $\phi(\eta)$ subjected to higher $Nt$ estimations. Physically, rise in thermophoresis force is viewed through higher $Nt$ parameter which frequently moves nanoparticles from higher towards lower temperature region. Thus, $\phi(\eta)$ enlarges. Effect of Biot number $\gamma$ on $\theta(\eta)$ is disclosed in Fig. 14. Heat transfer coefficient is included by parameter. Here, no heat transfer at wall is witnessed for zero Biot number and for added of Biot number improvement in boundary layer thickness is noticed. Result of Prandtl number $Pr$ on thermal field is disclosed in Fig. 15. In physical point of view, larger $Pr$ corresponds to low thermal
conductivity that reason a dwindle in heat conduction and thickness of the boundary. Thus, fluid temperature decays. The nanoparticles concentration curves \( \phi(\eta) \) for Schmidt number \( (Sc) \) estimations are plotted in Fig. 16. Larger \( (Sc) \) estimations yield \( \phi(\eta) \) diminishing. In physical point of view, mass diffusivity reduces when Schmidt number is increased. Thus, \( \phi(\eta) \) and boundary layer concentration of nanoparticles at the surface decays. Figs. 17-19 elucidates magnetic influence \( (M) \) on fluid flow, thermal energy and concentration profiles. Larger \( (M) \) enhances resistive Lorentz force in fluid which drags velocity surface and consequently dwindle flow profile are disclosed in Fig. 17 and 18 is portrayed effect of \( (M) \) on \( \theta(\eta) \). Here, thermal field upsurges via higher magnetic parameter. Physically, when Lorentz force rises reasons for resistance to nanofluid flow and therefore, the kinetic energy of nanoparticles increases. In consequences, \( \theta(\eta) \) escalates. Result of \( (M) \) on \( \phi(\eta) \) is addressed in Fig. 19. This graph exemplifies improvement in \( \phi(\eta) \). In fact, coefficient of mass transfer increases due to an upsurge magnetic parameter. The attributes of chemical reaction parameter \( (G) \) are exposed in Fig. 20. Here, we found lower \( \phi(\eta) \) subject to increase in \( (G) \). Such scenario is noticed because larger chemical reaction parameter implies destructive chemically species rate which liquefies liquid specie effectively. In consequence, \( \phi(\eta) \) lessens. Fig. 21 describes variations in thermal energy \( \theta(\eta) \) subjected to radiation parameter \( (R) \). This plot discloses \( \theta(\eta) \) improvement in energy for larger \( (R) \). physically, working nanofluid attains additional heat energy subject to radiation parameter. In consequence, \( \theta(\eta) \) upsurges.

The consequences of important pertinent parameters against the physical quantities of interest \( (Re_{\lambda}^{0.5} \; C_f, \; Re_{\lambda}^{0.5} \; Nu, \; Re_{\lambda}^{0.5} \; Sh) \) are particularized through Figs. 22–27. Figs. 22 and 23 report the influence of \( \varepsilon, \; M \; and \; \lambda \) on \( Re_{\lambda}^{0.5} \; C_f \). These graphs explain growth in skin fraction for larger estimations of \( \varepsilon \; and \; M \) whereas \( Re_{\lambda}^{0.5} \; C_f \) diminishes when \( M \; and \; \lambda \) are increased. The characteristics of \( Nb, \; Nt, \; Pr \; and \; R \) are plotted via Figs. 24 and 25. Clearly it is perceived that \( Re_{\lambda}^{0.5} \; Nu \) diminishes when \( Nb \; and \; Nt \) are augmented however opposing situation is observed for \( Pr \; and \; R \). Figs. 26 and 27 envisage \( Re_{\lambda}^{0.5} \; Sh \) analysis subjected to \( Nb, \; Nt, \; \lambda \; and \; Sc \). As anticipated \( Re_{\lambda}^{0.5} \; Sh \) enhance when these parameters are augmented.
Fig. 3. $\epsilon$ versus $f'(\eta)$

Fig. 4. $\epsilon$ versus $\theta(\eta)$
Fig. 5. $\epsilon$ versus $\phi(\eta)$
Fig. 6. $B$ versus $\theta(\eta)$

Fig. 7. $B$ versus $\phi(\eta)$
Fig. 8. $\lambda$ versus $\theta(\eta)$

Fig. 9. $\lambda$ versus $\phi(\eta)$
Fig. 10. Nb versus $\theta(\eta)$

Fig. 11. Nb versus $\phi(\eta)$
Fig. 12. $N_t$ versus $\theta(\eta)$

Fig. 13. $N_t$ versus $\phi(\eta)$
Fig. 14. $\gamma$ versus $\theta(\eta)$

Fig. 15. $Pr$ versus $\theta(\eta)$

Fig. 16. $Sc$ versus $\phi(\eta)$
Fig. 16. $Sc$ versus $\phi(\eta)$

Fig. 17. $M$ versus $f'(\eta)$
**Fig. 18.** $M$ versus $\theta(\eta)$

**Fig. 19.** $M$ versus $\phi(\eta)$
Fig. 20. $G$ versus $\phi(\eta)$

Fig. 21. $R$ versus $\theta(\eta)$
Fig. 22. \( (Re_x)^{1/2} C_{f_x} \) versus \( M \) and \( \varepsilon \)

Fig. 23. \( (Re_x)^{1/2} C_{f_x} \) versus \( M \) and \( \lambda \)
Fig. 24. \((Re_x)^{1/2} Nu_x\) versus \(Nb\) and \(Nt\)

![Graph showing \((Re_x)^{1/2} Nu_x\) versus \(Pr\) and \(R\)]

Fig. 25. \((Re_x)^{1/2} Nu_x\) versus \(Pr\) and \(R\)

![Graph showing \((Re_x)^{1/2} Nu_x\) versus \(Sh_x\) and \(Nb\) and \(Nt\)]
In this study, numerical solution of Prandtl nanofluid flow with a vertically heated stretching sheet with thermal radiation, heat source, and MHD is analyzed. The boundary layer flow yields constitutive (PDEs) which were altered to the corresponding dimensionless nonlinear (ODEs) via similarity transformations. The system was solved numerically using the bvp4c technique. The outcomes are presented graphically with numerous system parameters. Following are the leading findings of this investigation have been observed:

- It is perceived that fluid velocity augmented subject higher fluid parameter, whereas this parameter depicts an opposing appearance versus thermal field and concentration profile.
- Larger unsteady parameter yields enhancement in thermal energy and concentration of the nanofluid.

5. Conclusion

In this study, numerical solution of Prandtl nanofluid flow with a vertically heated stretching sheet with thermal radiation, heat source, and MHD is analyzed. The boundary layer flow yields constitutive (PDEs) which were altered to the corresponding dimensionless nonlinear (ODEs) via similarity transformations. The system was solved numerically using the bvp4c technique. The outcomes are presented graphically with numerous system parameters. Following are the leading findings of this investigation have been observed:

- It is perceived that fluid velocity augmented subject higher fluid parameter, whereas this parameter depicts an opposing appearance versus thermal field and concentration profile.
- Larger unsteady parameter yields enhancement in thermal energy and concentration of the nanofluid.
Similar features are witnessed qualitatively for larger thermophoresis versus temperature and solutal fields.

Higher Brownian motion parameter escalates fluid particles movement that developed the fluid temperature and fluid particles starts rapidly down from higher to lower regions.

Magnetism influence diminishes the velocity stream significantly, whereas reverse trends for temperature and nanoparticles concentration observed.

Larger Hartman number/magnetic parameter yields diminishes the surface drag force.

Data availability statement

The data used to support the findings of this study are included within the article.

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Authors Contribution Statement

H.R and Z.K wrote main manuscript file S.I and W.K give simulation of the problem. All authors contributed equally.