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A Comprehensive Review of Thermophoresis Particle Effects on Convective Heat Transfer and Climate Change Implications: Study of the Combined Characteristics

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Abstract. The main focus of the current study is to present a detailed review the impact of thermos physical properties of convective heat transfer in different fluids by taking insight from the previous literature. Further, the second aim is to provide a strong ground of study for scholars, and scientists those are working in this field. The main source of thermophoretic particles is the fossil fuels that released the thermophoretic particles such as carbon dioxide, methane, Black Carbon and many others. Since the thermophoresis particles are acidic and submicron in size, they can contribute to climate change by altering weather patterns and raising atmospheric temperatures. This study will give a clear insight to the researchers how the classical research is important to establish new theories and innovations in the field of thermal fluid science. The main novelty of the current review is to discuss the combined characteristics of thermophoretic particles for different aspect of heat and mass transfer issues. This study highlights the importance of these tiny/small particles in newly emerging issue of global warming in current literature. Additionally, the introduction section provides a thorough explanation of several elements of the thermophoresis particle's features based on information gathered from the literature.

2020 Mathematics Subject Classifications: 80A19

Key Words and Phrases: Thermal performance, thermophoresis particles, convective heat transfer, climate change, combined characteristics of thermophoretic particles

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1. Introduction

The mechanism in which a number of tiny particles are removed from the heated surface or come towards the cold surface due to the temperature difference is known as thermophoretic transportation or small nano -particle material motion. These Small particles can be dust particles when they are suspended in a gas or air that has a temperature difference experience a force which is opposite in the direction of the temperature gradient is called thermophoretic force. This phenomenon has diverse applications in nature and industry and in today very emerging issue of climate change. In the review, the main focus is to incorporate on the effect of thermophoretic motion and their combine thermos-physical characteristics in terms of literature review. Gunji et al. [1] examined the thermophoretic deposition in a turbulent tube, focusing on how aerosol particles deposit along the pipe length across different velocities. The thermophoretic transport of fine particles was discussed in the MCVD process [2] and through buoyancy-induced convective flow from a vertical plate [3]. In [4], Loyalka explored the impact of thermophoretic transport on an individual particle using a numeric solution of the linearized Boltzmann equation. Kang and Greif [5] observed a significant decline in deposition efficiency with higher gas stream speed and when the torch was not aligned with the target during the OVD process. Sung and Sang [6] inspected the transport of thermophoretic particles in a uniform tube stream, taking into account the impact of particle mass fraction and isotopic scattering. By using the method of reflection, Chen [7] numerically analyzed the thermophoretic aggregation of tiny particles with uniform temperature. It is concluded that the interactions may have a more pronounced impact on thermophoretic aggregation compared to sedimentation. Particle deposition due to thermophoresis in laminar and turbulent duct flow plays an important role in understanding how particles interact with the fluid dynamics and influence the quality and efficiency of the atmosphere and various engineering systems [8].

Chamkha and Pop [9] discussed the buoyancy-induced convective flow over an upright plate fixed in an absorbent medium, considering the deposition effects. Later on, Chamkha et al. [10] incorporated the impact of heat generation and compared their results with previous findings. Postelnicu [11] expanded on the research of Chamkha and Pop [9] and discussed the results for a horizontal plate. The approximation technique FDM was used to obtain numerical results, which were then presented graphically. In this study, we investigate the effect of thermophoresis on particle deposition in porous media, focusing on its complex interaction with Brownian motion [12, 13]. The impact of diffuso-thermal and thermo-diffusion effects on buoyancy-induced convective heat and mass transfer above an elongating surface, considering thermophoretic deposition, was evaluated by Siva Raman et al. [14] using group theory transformation. Natural convection in nanofluids where thermophoresis and Brownian motion effects play a significant role in nanofluid heat transfer enhancement [15]. Later on, Pal and Mondal [16] examined the influence of thermophoresis and Soret–Dufour effects on MHD flow over a wedge with variable temperature, incorporating Joule heating and thermal radiative energy. They obtained numerical results using the local non-similarity technique.

The influence of inconstant viscosity on combined free–forced convection over a wedge was discussed in [17]. The study of convective heat transfer characteristics was carried out via a round tube, and the complex effects of nanoparticles and thermophoresis in the behavior of the vertical and horizontal configuration of the plate were discussed in [18, 19]. In [20], Alam et al. inspected the influence of inconstant fluid properties on time-dependent 2D convective flow past a permeable elongating wedge. In [21–23], it was investigated how the wall slip and thermophoretic behavior of nanoparticles affect the convective heat transfer enhancement of nanofluids flowing through microchannels, a vertical cylinder, and porous media. Bhusnoor et al. [24] analyzed the thermophoretic deposition of sodium chloride and diesel engine exhaust in streamlined flow through a pipe with a temperature that declines axially. Li and Keh [25] employed a semi-analytic method to study the thermophoretic motion of spherical particles situated at arbitrary positions in a gas within a spherical enclosure, focusing on the impact of material properties. The problem of the thermophoretic effect caused by nano-spherical particles within the free molecular region was explored in [26]. Yin et al. [27] numerically investigated the deposition of nanosized particles influenced by Brownian and thermophoretic forces. They concluded that Brownian force has a greater impact on tiny particles, while the thermophoretic force is the primary factor affecting the deposition of large particles. An Analysis of thermophoresis and Brownian motion effects on heat transfer in a nanofluid-immersed distribution transformer with variable properties is given in [28–30]. The study on the transport and deposition of particles utilizing an adapted Markov chain model was introduced by Xiong and coauthors [31]. Malay et al. [32], Saad et al. [33], Cheng et al. [26], Faltas et al. [34], Sharaf et al. [35], Sun et al. [36] and El Sapa et al. [37] conducted a study on the motion of small nano-particle material in various fluids, accounting for diverse geometries. Tseng and Keh [38] discussed the thermophoresis of round cylindrical shaped particles at nonzero Peclet number. They obtained the numerical results using the perturbation technique. Ashraf et al. [39] numerically examined the impact of thermophoretic motion and heat absorption/generation past the sphere's surface. Their findings revealed that elevating heat generation raises the fluid temperature at certain locations on the surface.

In [40–42] the impact of thermophoretic motion on convective heat transfer round a spherical-shaped surface, taking into account various fluid properties was explored. Transient numerical analysis of thermophoresis and particle dynamics in a nanofluid pool boiling conditions and magnetohydrodynamics convective heat transfer was discussed in [43, 44]. Ashraf and coauthors [45–47] investigated the different characteristics of heat and fluid flow mechanism at various locations surrounding a sphere. They examined the impact of dissipation and thermophoretic motion and the flow geometry is given in Fig. 1. Keeping in view the above literature review we have the following details of the thermal properties of the thermophoretic convective heat transfer and their impact on climate change. The convective heat transfer processes for jet slip flow [48], magneto Walters-B nanofluid [49], electrophoretic and thermophoretic effects [50], thermophoretic hybrid nanofluid [51] and heat generation effects [52] are discussed. Flow of Maxwell fluid with heat transfer through porous medium with thermophoresis particle deposition and Soret–Dufour effects [53], chemical reaction of thermophoretic, titanium dioxide [54], water based nanofluid magneto thermophoretic [55] are discussed. Periodical analyses of convective heat transfer along electrically conducting cone embedded in porous medium [56], a non-conducting circular cylinder [57], Fourier's Ficks law [58], and magneto exothermic catalytic chemical reaction [59] were conducted. Heat and mass transfer analysis of a fluid flow across the conical gap of a cone-disk apparatus under the thermophoretic particles motion [60], magnetohydrodynamics micropolar nanofluid [61], thermophoretic particle deposition [62], Sutter by fluid capturing [63], and thermophoretic impacts over moving thin needle [64] has been predicted. Effect of nanoparticle diameter in Maxwell nanofluid flow with thermophoretic particle deposition [60], inclined plate with Joule heating [65], optically dense grey nanofluid [66], reduced gravity effects on transient fluid [67] has been investigated. The study examines how changes in viscosity and thermal conductivity can affect thermal dynamics and atmospheric conditions as it investigates the effects of thermophoretic convective heat transfer from fossil fuels on climate change [68, 69]. Thermal design of a non-isothermal microfluidic channel for measuring thermophoresis [70], heat transfer between coaxial pipes [71], thermophoretic particle deposition across disc [72], Darcy radiative flow past rotating cone [73] is discussed. A numerical study of the effect of graphene nanoparticle size on brownian displacement, thermophoresis, and thermal performance of graphene/water nanofluid by molecular dynamics simulation [74], determinanatal effect of thermal exposure [75], heat transmission permeability [76], and combined effects of heat source and aligned magnetic field [77] has been analyzed.

Computational study on the effects of Brownian motion and thermophoresis on thermal performance of cross fluid with nanoparticles in the presence of Ohmic and viscous dissipation in chemically reacting regime [78], entropy generation minimization [79], thermophoretic particle deposition on ZnO [80] and double diffusion [81] has been investigated. Impact of Viscous Dissipation and Ohmic Heating on Natural Convection Heat Transfer in Thermo-Magneto Generated Plume [82], thermophoretic particles deposition in ternary hybrid nanofluid with local thermal non-equilibrium conditions [83], thermophoresis and Brownian motion influenced bioconvective heat transfer [84] has been investigated. Thermo-particle heat transfers through stationary sphere and using plume, thermophoretic effect and convective thermal conditions on flow of hybrid nanofluid over a moving thin needle has been discussed in [85]. Nabwey et al. [86] highlighted previous studies on the fundamental concepts of convective heat transfer, such as how humidity influences buoyancy, airflow patterns, and thermal conductivity. Ashraf [87] investigated the thermophysical properties of heat and fluid movement, highlighting their significance in comprehending the environmental repercussions and implications. Iqbal et al. [88] addressed the interaction of a thermally radiative bioconvective nanofluid with microorganisms and thermophoretic particle deposition on a sheet, using a non-uniform heat source. Nadeem et al. [89] looked at the effects of thermophoretic particles formed during the burning of fossil fuels in the presence of catalytic chemical processes in the source region and heat sinks in the plume region on a bi-stratified atmosphere, with a particular emphasis on climate change. Joseph et al. [90] investigated the thermophoresis and Brownian motion effects of a diffusional heat-generating MHD Jeffrey nanofluid along an inclined vertical cone in a permeable medium including chemical processes and radiation. Jansen et al. [91] performed experiments with the thermophoretic force on particulates in the transition phase of rarefied flows. Swami et al. [92] studied the thermal and flow properties of hybrid nanofluids in free-forced convection with suction/blowing effects. The main novelty of the current work in this study is showing by relating how thermophoresis particles impact the climate change and shift the weather pattern.

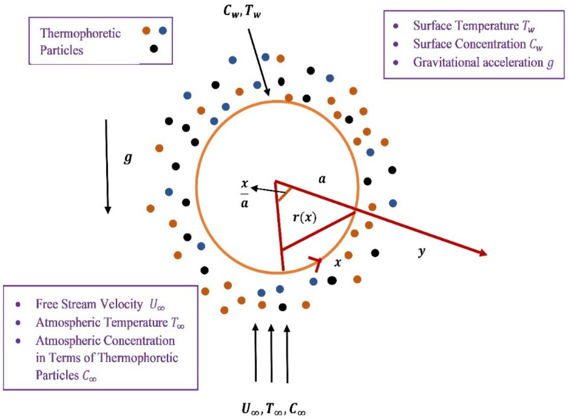


Figure 1: Flow geometry.

The main mathematical model used in [45–47] for which they have discussed different characteristics of thermophoretic motion is given as below:

$$\frac{\partial(ru)}{\partial x} + \frac{\partial(rv)}{\partial y} = 0 \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + \lambda_t\,\theta\sin x + \lambda_c\,\phi\sin x \tag{2}$$

$$u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y} = \frac{1}{\mathrm{Pr}}\frac{\partial^2 \theta}{\partial y^2} \tag{3}$$

$$u\frac{\partial \phi}{\partial x} + v\frac{\partial \phi}{\partial y} = \frac{1}{\mathrm{Sc}}\frac{\partial^2 \phi}{\partial y^2} - \frac{\partial\big(v_t\,\phi\big)}{\partial y} \tag{4}$$

$$\begin{aligned} &u = 0, \quad v = 0, \quad \theta = 1, \quad \phi = 1 && \text{at } y = 0, \\ &u \to 1, \quad \theta \to 0, \quad \phi \to 0 && \text{as } y \to \infty. \end{aligned} \tag{5}$$

Here, r is the radius of the circle, while x and y denote the distances along and normal to the sphere, respectively. Furthermore, λ_t and λ_c represent the mixed convection and modified mixed convection parameters, respectively. Whereas, Pr and Sc denote the Prandtl number and Schmidt number, respectively.

2. Results and Discussion in Terms of Combined Characteristics

The current review based on the review of the thermophysical properties and their impacts on different physical quantities; the Fig. 2 highlights the main structure of review which is given as below:

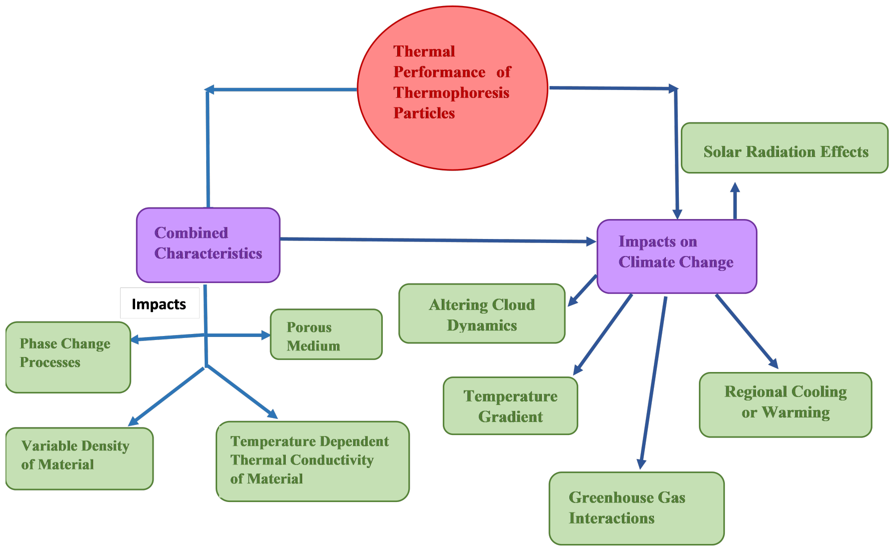


Figure 2: Flow Chart of the main thermophysical properties and impacts on climate change.

2.1. Impact of thermophoretic convective heat transfer in porous medium

In porous medium the momentum of thermophoretic particles due to convective heat transfer can alter the porosity and permeability in the porous medium region. In the above said medium where the combustion or chemical reactions take place, the thermophoretic particles can impact the spreading of chemical reactants and, thus, impacting the rate of reaction and heat transfer release configurations. Such kind of mechanisms are especially relevant in catalytic chemical reactions or in the porous burneries regions where the fine particles are present. To analyze the optimization of the heat transfer performance and system design in porous medium the understanding of the impacts of thermophoretic convective heat transfer is important. In purifying procedures involving porous medium, thermophoresis is essential because it can affect how well fine particles are captured. It is also noted that in the aerosol movement within porous structures regions, the thermophoretic forces can impact the removal patterns and the change the heat transfer properties. Thus, the thermophoretic convective heat transfer in porous medium can have a considerable impact for modifying the material properties and varying the thermal characteristics of heat and fluid flow mechanism. The detailed study is given in [67].

2.2. Impact of Thermophoretic Convective Heat Transfer on Phase Change Processes

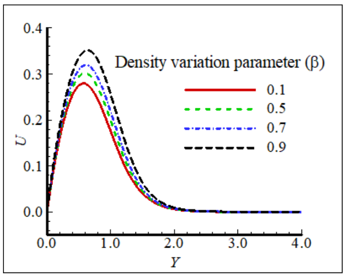
Further, it is observed that the cases where the phase changes mechanism is occurred due to the porous medium such as material condensation or evaporation, the thermophoretic convective heat transfer can influence the rate and position of these phase changes processes. It can also impact the latent heat transfer processes and overall energy balance system in the phase change regions. It is also noted that the thermophoretic convective transport process can shift the phase change front within the porous medium region. In this mechanism the front phase of the system can either stretched or shrink in the overall phase change mechanism. It depends on the direction of particle motion and the prevailing temperature gradients of the system under consideration.

2.3. Impact of Variable Density of the Material on Thermophoretic Convective Heat Transfer

A very important property of the heat and fluid flow mechanism is the variable density. Here, we highlight the impact of variable density on thermophoretic convective heat transfer. In heat and fluid flow mechanism where the density of the material is variable, thermophoretic small particles can have significantly influence on the convective heat transfer process. From the closed observation of the literature, it is noted that the variations in density of the material resulting to change in the flow dynamics that is buoyancy effects, and temperature gradients, and all these dynamics impact the heat and fluid flow performance and their characteristics in terms of convective heat transfer. In environmental engineering the understanding of thermophoretic convective heat transfer is important to predict the motion of pollutant particles and particulate the matters in the atmosphere, especially in the existence of thermal gradients. In industrial processes such as removal of aerosol, combustion, and filtration, thermophoretic effects can be coupled or need to be moderated depending on the desired product in the presence of variable density of the material. We summarize the involvement of property variable density in heat and fluid processes that the thermophoretic convective heat transfer can have a significant role to determine the efficiency and behavior of heat transfer dynamics for wide range of applications in engineering and as well as in environmental sciences. The impact of different values of density variable parameter on velocity profile and temperature profile are given in Fig. 3.

2.4. Impact of Temperature Dependent Thermal Conductivity of the Material on Thermophoretic Convective Heat Transfer

Thermal conductivity is a material characteristic which measured the tendency of a material to transmit energy through it. For many constituents, thermal conductivity is temperature-dependent, it means that the heat transmits tendency changes as the temperature of the material is changed. It can be linear, exponential or may be other some complex relationships, it depends on the material characteristics and temperature absorb-



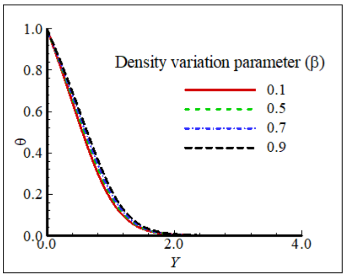


Figure 3: The impact of different values of density variation parameter, β, on velocity profile, temperature profile.

ing behavior. If with the increasing temperature the thermal conductivity of the material is increased, the material turns into more efficient to conduct heat at higher temperature difference. Thus, the temperature of the system during processes is increased, particularly, in the region where temperature gradient is large. On the other hand, if the thermal conductivity of the material is decreased as the function of temperature, the material's tendency to transmit energy through it is mitigate, the overall potential of heat transfer in the system is reduced. If the system is strongly temperature dependent, then the thermal conductivity of the material leads to non-linear temperature gradients behavior within the fluid and consequently, this non-linearity can impact the contribution of thermophoretic forces and, the motion of thermophoretic particles. The situations where particle removal because of thermophoretic is critical, like coating processes or pollutant control, consequently, the temperature dependent thermal conductivity can impact the deposition form of the system. Material for which the thermal conductivity having more uniform deposition for decreasing thermal conductivity could lead to irregular thermophoretic particle contribution in the system. From this it is concluded that the effect of temperature-dependent thermal conductivity on thermophoretic convective heat transfer is complicated. It can impact the rate of heat transfer, changes temperature slope, impact boundary layer mechanism, and alter particle deposition forms. From this understanding, it is very clear that the optimization of heat transfer processes due to temperature dependent thermal conductivity is very crucial in different engineering applications to design the heat exchanger systems and for the prediction of thermal performance of the system. Ashraf et al. in [42], highlighted the impact of thermal conductivity variation on heat and mass transfer and are given in Table 1 and Fig. 4.

2.5. Impact of Temperature Dependent Dynamic Viscosity of the Material on Thermophoretic Convective Heat Transfer

From the natural and industrial processes, it is observed that the effect of temperature-dependent dynamic viscosity on thermophoretic convective heat transfer is significant and reasonable in many scientific and engineering applications, especially in systems where the temperature gradients are dominant and impactful. Keeping in view the thermo-physical characteristics of the dynamic viscosity of a fluid, it is noted that the dynamic viscosity

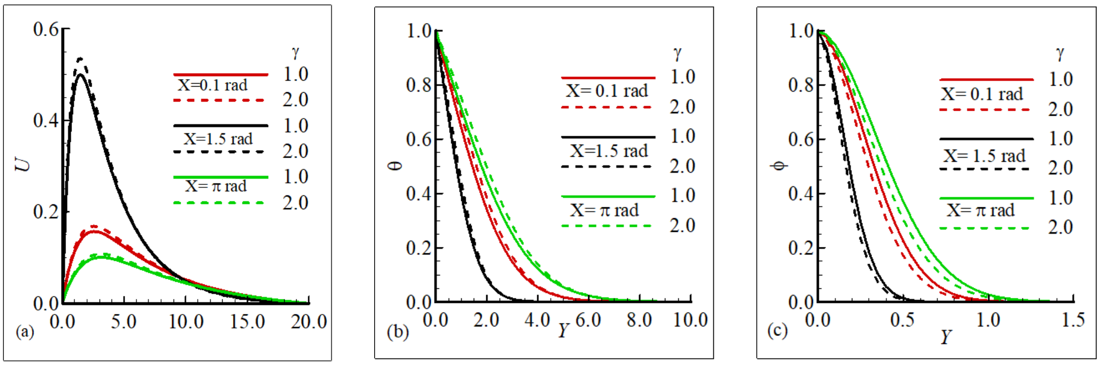


Figure 4: The impact of different values of thermal conductivity variation parameter, γ, on velocity profile, temperature profile and mass concentration.

Table 1: The Impact of Different Values of Thermal Conductivity Variation Parameter, γ, on Skin Friction, Rate of Heat and Mass Transfer.

	$\frac{\partial U}{\partial Y}$		$\frac{\partial \theta}{\partial Y}$		$\frac{\partial \phi}{\partial Y}$	
X	$\gamma = 0.1$	$\gamma = 2.0$	$\gamma = 0.1$	$\gamma = 2.0$	$\gamma = 0.1$	$\gamma = 2.0$
$\frac{\pi}{30}$	0.32472	0.32522	0.47826	0.47283	0.00034	0.00035
$\frac{\pi}{2}$	1.82527	1.82866	0.85071	0.84104	0.00054	0.00056
π	0.16821	0.16852	0.38390	0.37954	0.00027	0.00028

of the fluid is decreased for the increasing behavior of temperature. As viscosity decreases with temperature, the fluid experiences reduced resistance to flow. From the study of above literature, it is established that for the increasing temperature of dynamic viscosity leads to a thinner boundary layer thickness and is increased the speed of fluid flow and thus impact the shear stress contribution in the system under consideration. Further, it is noted that due temperature-dependent viscosity effects the thermophoretic velocity of particles in the domain under consideration. As the fluid's viscosity is decreased for the increasing values of temperature, the particles can experience low confrontation to their motion, and thus augmented the thermophoretic impact in the heat and fluid flow mechanism. Due to the effect of temperature dependent viscosity the motion of particles is affected and thus thermophoretic motion in the heat and fluid flow regime is enhanced and can lead to improve heat transfer mechanism where the momentum of thermophoretic particles play a vital role. In many engineering applications the understanding of temperature dependent dynamic viscosity is very important for the designing of systems involving thermophoretic convective heat transfer mechanisms. It is important for the selection of material to design the heat exchanger systems and for the prediction of thermal performance of the system. Amir et al. [40] highlighted the impact of property variation temperature dependent viscosity on heat and fluid flow mechanism in the presence of thermophoretic motion as shown in Table 2 and Fig. 5.

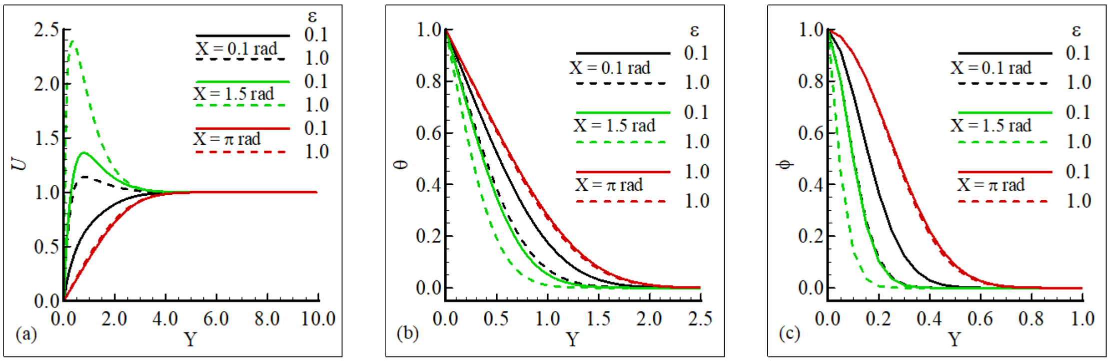


Figure 5: Variation of temperature dependent dynamic viscosity parameter ε, by keeping constant double diffusion parameter and taking thermophoresis parameter $N_t = 10.0$.

Table 2: Variation of Temperature-Dependent Dynamic Viscosity Parameter ε, Keeping Constant Double Diffusion Parameter and Taking Thermophoresis Parameter $N_t = 10.0$.

	$\frac{\partial U}{\partial Y}$		$\frac{\partial \theta}{\partial Y}$		$\frac{\partial \phi}{\partial Y}$	
X	$\varepsilon = 0.1$	$\varepsilon = 1.0$	$\varepsilon = 0.1$	$\varepsilon = 1.0$	$\varepsilon = 0.1$	$\varepsilon = 1.0$
$\frac{\pi}{30}$	23.63814	8.03512	0.77412	1.63644	0.06366	0.00673
$\frac{\pi}{2}$	110.71127	35.88113	1.27044	2.77247	0.16246	0.01324
π	0.49242	0.36245	0.43442	0.89074	0.00216	0.00027

2.6. Impact of Thermophoretic Particles on Climate change

Thermophoresis can influence the distribution of aerosols in the atmosphere. Aerosols, such as dust, soot, and volcanic ash, can be redistributed vertically and horizontally. This redistribution can affect cloud formation, the radiation balance, and precipitation patterns. One example of thermophoretic particles is black carbon particles absorbs the electromagnetic rays which can warm the atmosphere and cool the surface of earth. Thus, the momentum of these particles are depends on type and location which can lead to localized the cooling or warming in terms of climate change. Further, in the polar region the thermophoretic particles in the form of black carbon are deposited and settled on the ice surface and can cause the heavy floods. The contribution of aero soil can affect air quality particularly in big and populated cities. It leads to bad impacts on human health and ecosystem. We summarize that the thermophoretic particles can play a vital role in the complex interactions between thermophoretic aerosols and climate. Thus, this mechanism influences the spreading of particles, which can have cascading impacts on radiative forcing, cloud characteristics, regional climate system, and ultimately, global climate change in terms of global warming. The impact of thermophoresis parameter on temperature flow from Nadeem et al. [69] are given in Table 3 and Fig. 6.

On the basis of above literature review, we can claim that the environmental factors like cloud formation can be greatly influenced by thermophoretic particles, which move in

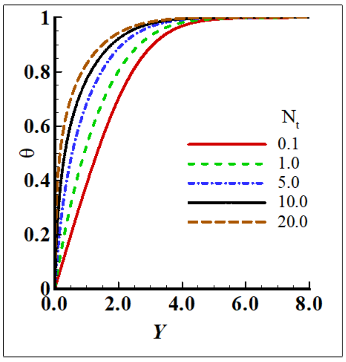


Figure 6: The impact of thermophoretic parameter on temperature distribution.

Table 3: Computational Findings of the Impact of Thermophoresis Parameter N_t on Heat Transfer in Heated Atmosphere.

N_t	Heat Transfer
0.1	0.32791
1.0	0.31684
5.0	0.30129
10.0	0.29081
20.0	0.27351

response to temperature gradients. The distribution of aerosol particles in the atmosphere can be changed by thermophoretic forces. These aerosols are essential for the processes of ice nucleation and cloud condensation. Thermophoretic particles can impact cloud microphysics by altering aerosol size and concentration. The development of ice crystals in clouds can be aided by thermophoretic particles acting as ice nucleating agents. Changes in cloud characteristics, like cloud duration and precipitation efficiency, may result from this. These particles have the potential to produce smaller cloud droplets, which could postpone rainfall but intensify it when it does happen. The movement of thermophoretic particles can enhance heat transfer in the atmosphere, impacting local temperature gradients. This can influence weather patterns and the development of different cloud types. Changes in temperature distribution can also affect the stability of the atmosphere, potentially leading to more severe weather events. Thermophoretic particles may have wider effects on climate systems by changing precipitation and cloud formation patterns. By altering the amount of solar radiation that clouds absorb or reflect, they can have an impact on the radiative balance of the Earth.

Renewable energy and entropy generation minimization (EGM) are related ideas that have a big impact on real-world and environmental applications. The practical and environmental results are greatly influenced by the combined properties of renewable energy and entropy generation minimization such that these ideas are cleaner energy, more sustainable energy future by emphasizing efficiency, sustainability, and innovation. The study of thermophoretic particles benefits from both experimental and computational methods, each of which offers distinct information and insights. Accurately modeling these processes and forecasting their consequences in a variety of applications, such as atmospheric science, pollution control, and material science, requires an understanding of the parameters influencing particle deposition and movement. Predictive abilities in real-world situations can be improved and thermophoretic behavior can be better understood by combining experimental data with computer models.

3. Conclusion

In the current study, a comprehensive review of the thermo-physical properties of thermophoretic convective heat transfer and its impacts on climate change is presented for the general understanding of researchers, academicians, and scientists who are involved in both theoretical and experimental research in the field of heat and fluid flow. From the close observation of the literature review and the different characteristics discussed above, we summarize the study in the following few lines. Thermophoresis plays a critical role in filtration processes within porous media, where it can influence the capture efficiency of fine particles. The thermophoretic convective heat transfer in a porous medium can have a considerable impact on modifying the material properties and varying the thermal characteristics of heat and fluid flow mechanisms. It is observed that in cases where phase change mechanisms occur due to the porous medium—such as material condensation or evaporation—the thermophoretic convective heat transfer can influence the rate and position of these phase change processes. We summarize that the involvement of property-variable density in heat and fluid processes indicates that thermophoretic convective heat transfer can play a significant role in determining the efficiency and behavior of heat transfer dynamics across a wide range of applications in engineering as well as in environmental sciences. It is concluded that the effect of temperature-dependent thermal conductivity on thermophoretic convective heat transfer is complex. It can impact the rate of heat transfer, change the temperature gradient, affect the boundary layer mechanism, and alter particle deposition forms. From this understanding, it is evident that optimizing heat transfer processes under temperature-dependent thermal conductivity is crucial in various engineering applications. We summarize that thermophoretic particles can play a vital role in the complex interactions between thermophoretic aerosols and climate. This mechanism influences the spreading of particles, which can have cascading impacts on radiative forcing, cloud characteristics, regional climate systems, and ultimately, global climate change in terms of global warming.

Future investigations could focus on (i) exploring the effects of variable density under non-linear and transient flow regimes, (ii) developing advanced numerical models that couple density variations with temperature and concentration gradients, and (iii) investigating experimental validation techniques using high-resolution flow visualization methods.

Author Contributions

All authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data are available upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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