**Entropy Generation Analysis of Magnetized Green Nanofluid Flow Over a Flat Plate: An Application to Parabolic Collectors**

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**Abstract.** Nanofluids are considered to be the smartest fuel for the future, yet the introduction of green nanofluids take this concept a step further. Green nanofluids are similar to existing nanofluids in every aspect, except they are derived from natural sources, making them more suitable as future coolants. This study explores the entropy generation in a parabolic trough solar collector when the system is exposed to a uniform-strength magnetic field applied perpendicular to the flow direction. Entropy generation is modelled using the second law of thermodynamics, accounting for the effects of heat transfer, radiation, Ohmic heating, and viscous dissipation. The expression governing the flow are solved using bvp4c solver in MATLAB. The study reports that magnetic field, viscous dissipation, and radiation parameters strongly influence irreversibility, while Richardson number increase entropy generation near the wall but reduces it farther away. These findings provide insights for optimizing thermal efficiency and reducing irreversibility in PTSC systems.

**INTRODUCTION**

The intensifying challenges of climate change, fossil fuel depletion, and escalating energy demand have driven an urgent global shift toward clean and renewable energy alternatives. Solar energy, among the most abundant and sustainable sources, stands at the forefront of this transition due to its environmental compatibility and scalability. In particular, Parabolic Trough Solar Collectors (PTSCs) have emerged as highly promising systems for medium-to high-temperature applications, offering reliable performance and integration potential in the industrial and power generation sectors [1]. However, the thermal efficiency of PTSCs is significantly constrained by the choice of heat transfer fluid (HTF). Conventional fluids such as water, oil, and molten salts exhibit limited thermal conductivity and often involve environmental trade-offs. This has led to increasing interest in nanofluids-colloidal suspensions of nanoparticles in base fluids-which show notable enhancements in thermal properties [2]. Yet, the use of traditional nanofluids often involves synthetic chemicals or toxic precursors, raising concerns about long-term environmental impact and sustainability [3]. The thermal performance improvement of nanofluid-based PTSC for sustainable environment applications was demonstrated by Farooq *et al.* [4]. The thermal efficiency improvement of a PTSC utilizing various copper absorber tube designs was discussed by Al-Rabeeah *et al.* [5]. Pahlavanian *et al.* [6] demonstrated a PTSC with variable heat flux based on different twisted tapes as a swirl generator using nanofluids with varying volume fractions. Khedher et al. [7] performed the energy, exergy, and environmental analyses in various absorber tubes of the EuroTrough-150 solar collector using non-Newtonian nanofluid. Panja *et al.* [8] investigated the effect of adding Al2O3 and CuO nanoparticles on heat transfer in a PTSC, especially when porous barriers are inserted into the receiver tube. Byiringiro *et al.* [9] worked on the durability and performance of PTSC systems utilizing Therminol VP-1 as the HTF.

Green nanofluids [10], by contrast, are synthesized using eco-friendly techniques and bio-compatible base fluids, such as vegetable oils or plant extracts, combined with naturally derived or low-toxicity nanoparticles. Okonkwo *et al.* [11] assessed the thermal efficiency of a parabolic trough collector utilizing green-synthesized nanofluids. The synthesized nanoparticles derived from green matter and agricultural waste were identified as effective corrosion inhibitors that are non-toxic and cost-efficient relative to traditional methods. Kumar *et al.* [12] examined the various approaches used in the manufacture of green nanofluids from various natural extracts, as well as their application in thermal systems. These fluids present a dual advantage: improved thermal conductivity and enhanced sustainability. Their lower environmental footprint, biodegradability, and potential for circular manufacturing make them especially attractive for renewable energy applications [13]. Green nanofluids have demonstrated superior energy efficiency, lower viscosity at high temperatures, and stable dispersion properties-ideal traits for solar thermal systems [14].

In the real world, usually the fluids do not behave like a Newtonian fluid; rather, they are non-Newtonian in nature. Among various non-Newtonian fluid models, the power-law formulation is widely used to describe shear-thinning as well as shear-thickening behaviour. For PTSCs utilizing green nanofluids, adopting a non-Newtonian framework provides a more realistic understanding of the transport phenomenon. Moreover, in solar thermal systems, fluid behaviour is not only influenced by shear effects but also by external forces and thermal field. Researchers have acknowledged the importance of these effects, and a wide range of literature is available on them. Andersson *et al.* [15] utilized exact similarity transformation to study the magnetized flow of power-law fluid over a stretching sheet. The flow of a thin film of power-law fluid over a non-uniformly stretching surface was investigated by Andersson *et al.* [16]. Denier and Dabrowski [17] conducted a thorough examination of the boundary-layer equations that regulate the rheology of a power-law fluid. Myers [18] studied boundary layer behaviour of power-law fluid flowing over a flat plate. The turbulence model for power-law fluid flow was solved by Gavrilov and Rudyak [19] using the elliptic relaxation technique. A laminar and incompressible magnetic flow of power-law fluid over a stretching surface with power-law slip velocity conditions and radiation was examined by Shamshuddin *et al.* [20]. The irreversibility and viscous heat loss of a power-law fluid's Jaffrey-Hamel flow within a wedge-shaped channel were measured by Rehman *et al.* [21].

While first-law efficiency (energy conservation) has long been the focal point of thermal system analysis, second-law efficiency-which accounts for irreversibility, is increasingly recognized as a more comprehensive performance metric. Entropy generation quantifies this irreversibility arising from viscous dissipation, Joule heating, and temperature gradients during fluid flow and heat transfer. Minimizing entropy generation directly correlates with improving system efficiency. Butt *et al.* [22] investigated how dissipation and thermal radiation affected the entropy generation in the Blasius flow. Malvandi *et al.* [23] computed the entropy generation for a 2D, steady boundary-layer flow of a nanofluid over a flat plate. Jouybari *et al.* [24] investigated the entropy generation for a flat plate solar collector. They discovered that the irreversibility of the pressure drops caused by fluid friction in the porous medium had no significant impact on the creation of entropy. The second rule of thermodynamics was applied to classical Blasius flow by Afridi and Qasim [25], taking into account the effects of frictional heating and nonlinear radiation. Rashidi *et al.* [26] analysed turbulent nanofluid flow in a solar heater duct with rib roughness on the absorber plate using the second law of thermodynamics. Ullah et al. [27] numerically examined the irreversibility and heat transfer in time-dependent free convection flow of a power law fluid across a vertical plate in the presence of a magnetic field. Khan et al. [28] examined the entropy generation in incompressible boundary layer flow caused by a heated flat plate with temperature-dependent viscosity. Koholé *et al.* [29] conducted a detailed exergy analysis of a flat-plate solar collector using irreversibility rates. Akbar *et al.* [30] examined entropy generation rate and peristaltic transport within a wavy duct using the Jeffrey fluid model because this fluid exhibits viscoelastic behaviour.

In view of the above-cited literature, it’s been observed that despite being the advancement in the development of nanofluid-based solar thermal systems, several key gaps still persist. There is no published work that has integrated the MHD, quadratic thermal radiation, and Ohmic heating on a quadratically convective flow of non-Newtonian (power-law) based green nanofluid (BH-SiO2/water) over a flat plate to investigate the entropy generation. However, individual aspects-such as MHD in power law fluids [15], entropy analysis of nanofluid [23,27], energy/exergy analysis in PTSCs [7] have been explored; a unified, coupled model remains largely unexplored. Existing research often treats these physical mechanisms in isolation, which limits the ability to capture complex interactions between electromagnetic forces, viscous and thermal dissipation, and nonlinear transport properties-factors that are all highly relevant in solar thermal environments utilizing advanced fluids.

In response to these gaps, this paper develops a comprehensive thermofluidic model that:

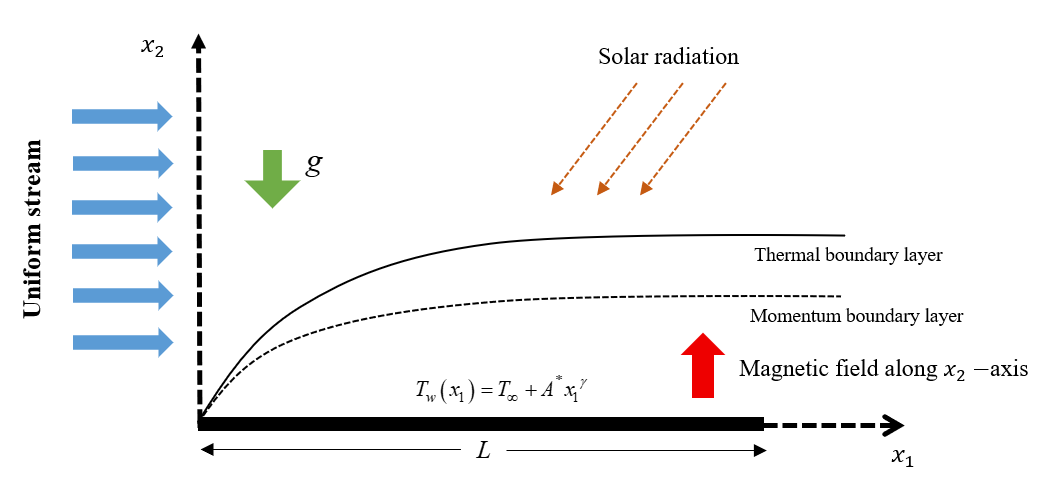
* Incorporates a power-law model for modelling the flow of green nanofluid over a flat plate specifically tailored for PTSC systems.
* Accounts for the combined influence of MHD, thermal radiation, non-linear convection, Ohmic heating, and variable surface temperature, capturing realistic operating conditions.
* Conducts a detailed entropy generation analysis to quantify thermodynamic irreversibility, utilizing parameters such as Bejan number to evaluate dominant entropy sources [26].

**PROBLEM DESCRIPTION AND MATHEMATICAL FORMULATION**

***Physical model and assumptions***

In PTSC, the heat transfer fluid flows inside a cylindrical receiver tube. To reduce modelling complexity, we assume the tube has a sufficiently large curvature such that its geometry can be approximated as a flat surface. This flat plate is oriented in the direction, with a homogenous magnetic field applied perpendicularly, along the axis, as depicted in Fig. 1.

Consider, a steady, laminar, and incompressible two-dimensional flow of a non-Newtonian nanofluid across a flat surface. The flow is generated by a temperature gradient over the surface and characterized by quadratic convective processes. The heat transfer within the fluid is governed by Fourier’s law, and is influenced by Ohmic heating and thermal radiation. The fluid under consideration is green nanofluid, here SiO2 nanoparticles extracted from Barely-husk (BH) are considered, which are dispersed in base fluid, water. The BH-SiO2/H2O nanofluid behaves as shear-thinning fluid, thus the problem is modelled using power-law fluid model [15-16], a non-Newtonian model.

**FIGURE 1.** Schematic representation of present flow model.

***Governing equations***

Based on the previously stated assumptions and the boundary layer approximation, the governing equations are formulated as [31-32]:

(1)

(2)

(3)

With the appropriate boundary conditions:

(4)

In above equations, refers to velocity components along and directions, flow consistency index, density, thermal expansion coefficients, wall temperature parameter, specific heat*,* electrical conductivity, thermal conductivity, Stefan–Boltzmann constant, mean absorption coefficient, gravity,  scaling factor constant, power-law index, is temperature, is wall temperature and is ambient temperature, respectively.

The thermophysical properties of the nanoparticle and water, as well as the correlation to compute the effective value of thermophysical properties can be accessed from [11, 33].

For the analysis, we introduce a stream function i.e., and . It satisfies the continuity equation. Moreover, the following similarity transformations and dimensionless temperature are defined as [32]:

, , (5)

Using transformation (5), the equation governing the flow are transformed to the following dimension free form:

(6)

(7)

with boundary conditions:

(8)

The symbols present in above equations are magnetic field parameter, Richardson number, non-linear convection parameter, Eckert number, radiation parameter, temperature ratio, modified Prandtl number and local Reynolds number, and are mathematically defined as:

and, are ratio of effective thermophysical properties of green-nanofluid to water.

***Entropy generation and irreversibility analysis***

The mathematical expression for the local volumetric rate of entropy generation in the present case is given as [22-23]:

(9)

This equation shows that entropy generation is mainly because of four main sources here, i.e., due to heat transfer, thermal radiation, viscous dissipation, and Ohmic heating. Now, defining a non-dimensional number namely entropy generation number associated to as:

(10)

where is the characteristics entropy generation rate. Using the preceding calculation for , the averaged may be assessed utilising the subsequent formula

(11)

where is the boundary layer region’s length. The Bejan number defined as “ratio of entropy generation due to heat transfer to the total entropy generation”, is another crucial irreversibility parameter:

(12)

**METHODOLOGY**

The previous section delineates the mathematical modelling of the examined flow problem, transforming the controlling partial differential equations into non-dimensional ordinary differential equations using similarity transformation. This section presents the methodology applied to solve these ODEs, here we have used bvp4c solver in MATLAB to obtained the solution of the equations (6)-(7) with (8).

The accuracy of the applied method is verified by comparing the values of , and with those reported by Cortell [34], see Table 1. And, for this we have neglected the heat transfer process, and compute the results for , when . It is noted from the table that the current findings align well with published ones.

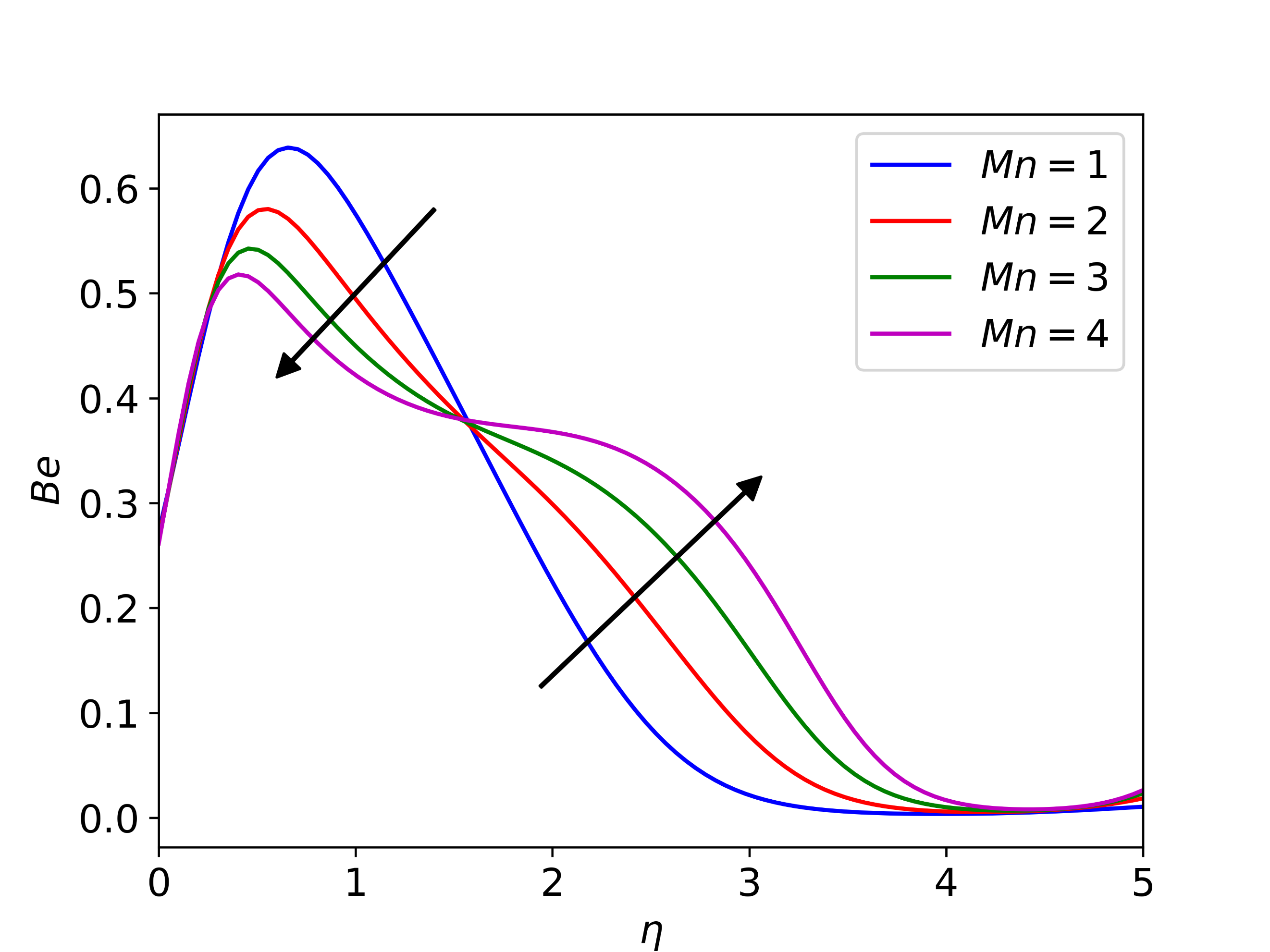
**TABLE 1.** Comparison of the , and values.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Cortell [34] | | | Present values | | |
|  |  |  |  |  |  |
| 0 | 0.00000 | 0.00000 | 0.33206 | 0.0000 | 0.0000 | 0.3321 |
| 1 | 0.16557 | 0.32978 | 0.32301 | 0.1656 | 0.3928 | 0.3230 |
| 3 | 1.39682 | 0.84605 | 0.16136 | 1.3968 | 0.8460 | 0.1614 |
| 5 | 3.28330 | 0.99155 | 0.01591 | 3.2833 | 0.9915 | 0.0159 |
| 7 | 5.27927 | 0.99993 | 0.00022 | 5.2792 | 0.9999 | 0.0002 |
| 9 | 7.27925 | 1.00000 | 0.00000 | 7.2792 | 1.0000 | 0.0000 |

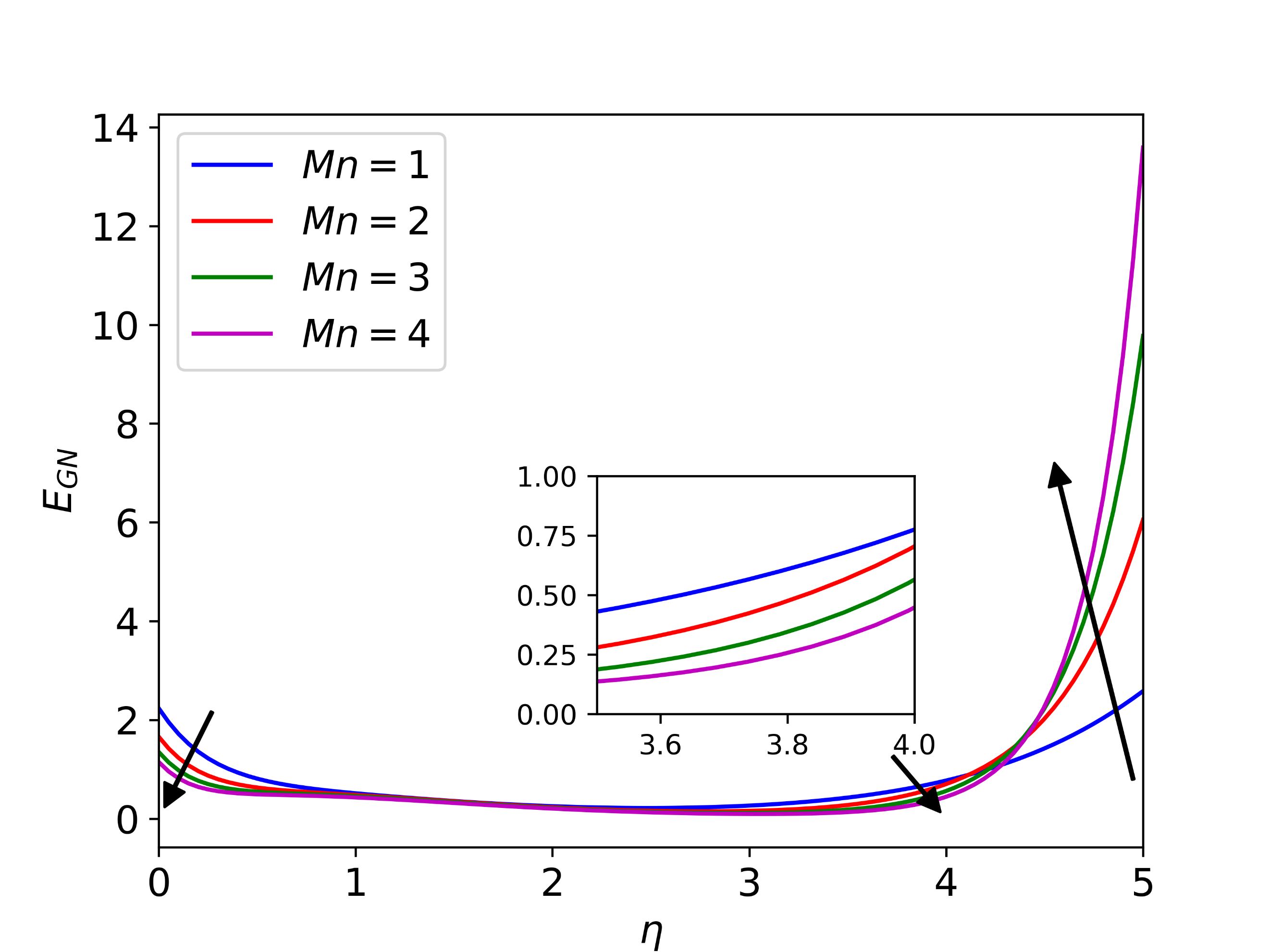
**DISCUSSION AND FINDINGS**

The preceding section outlines the applied methodology and code validation. This section presents a comprehensive discussion of the entropy generation number and Bejan number, as illustrated in Figs. 2-15, corresponding to parameter respectively. Here, the considered nanofluid is assumed to be behave like shear-thinning fluid thus the computation is done for , with the taken as 4.5946, with . And, the nanoparticle volume fraction is fixed at 2%.

Figures 2 and 3 presents the influence of growing on and with varying from 1 to 4. As we know, affects the flow field as well as temperature field, here presence of results in the generation of heating which also contributing in the entropy generation. Figure 3 shows that with increase in values, reduced in the regions and , while after it starts growing. And far away from the surface say , here maximum entropy generation is noted and among the considered values of , has maximum . On the other hand, in the region decreases and for it upsurges.

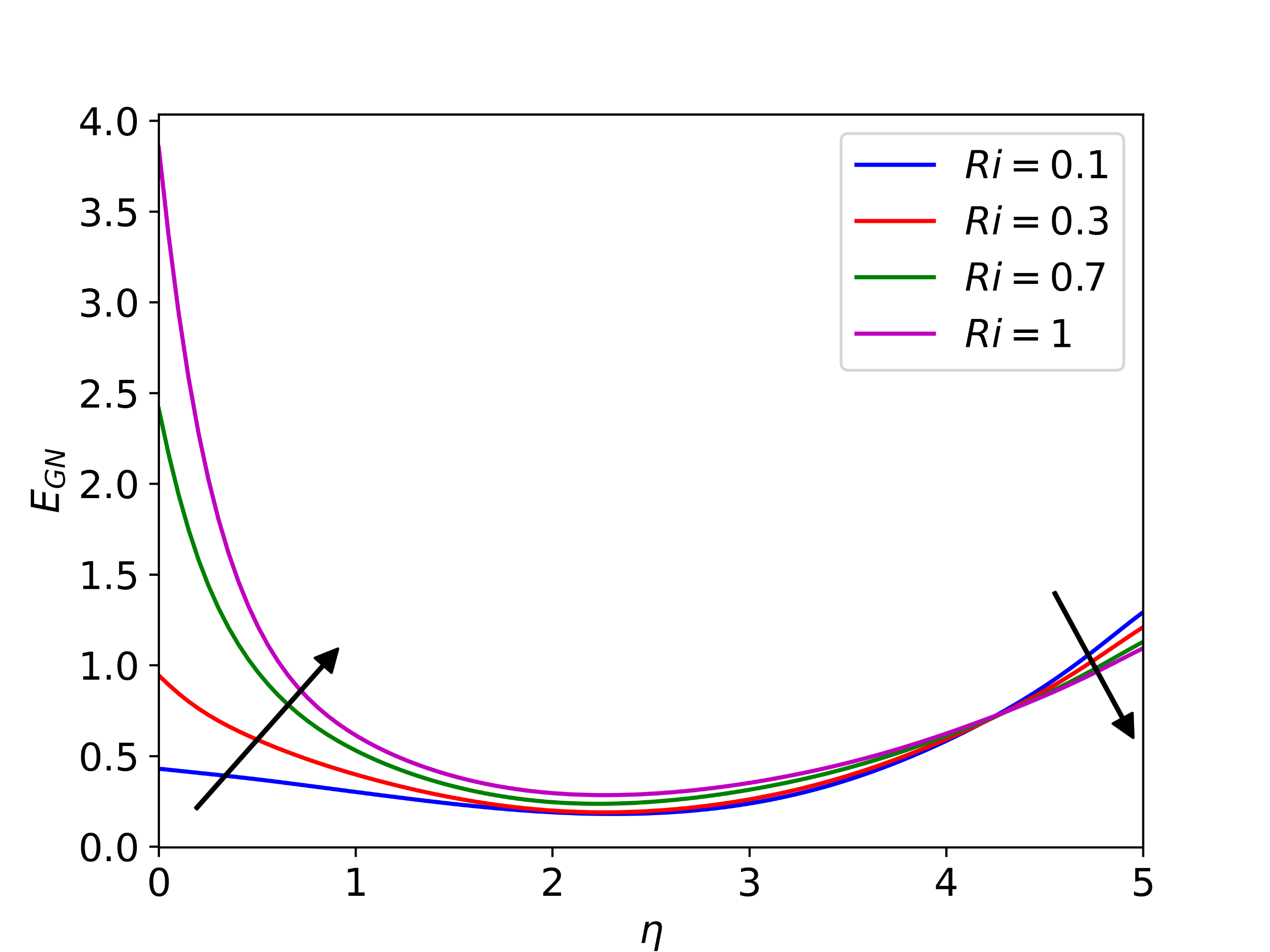


**FIGURE 3.** Variation of profiles for different .

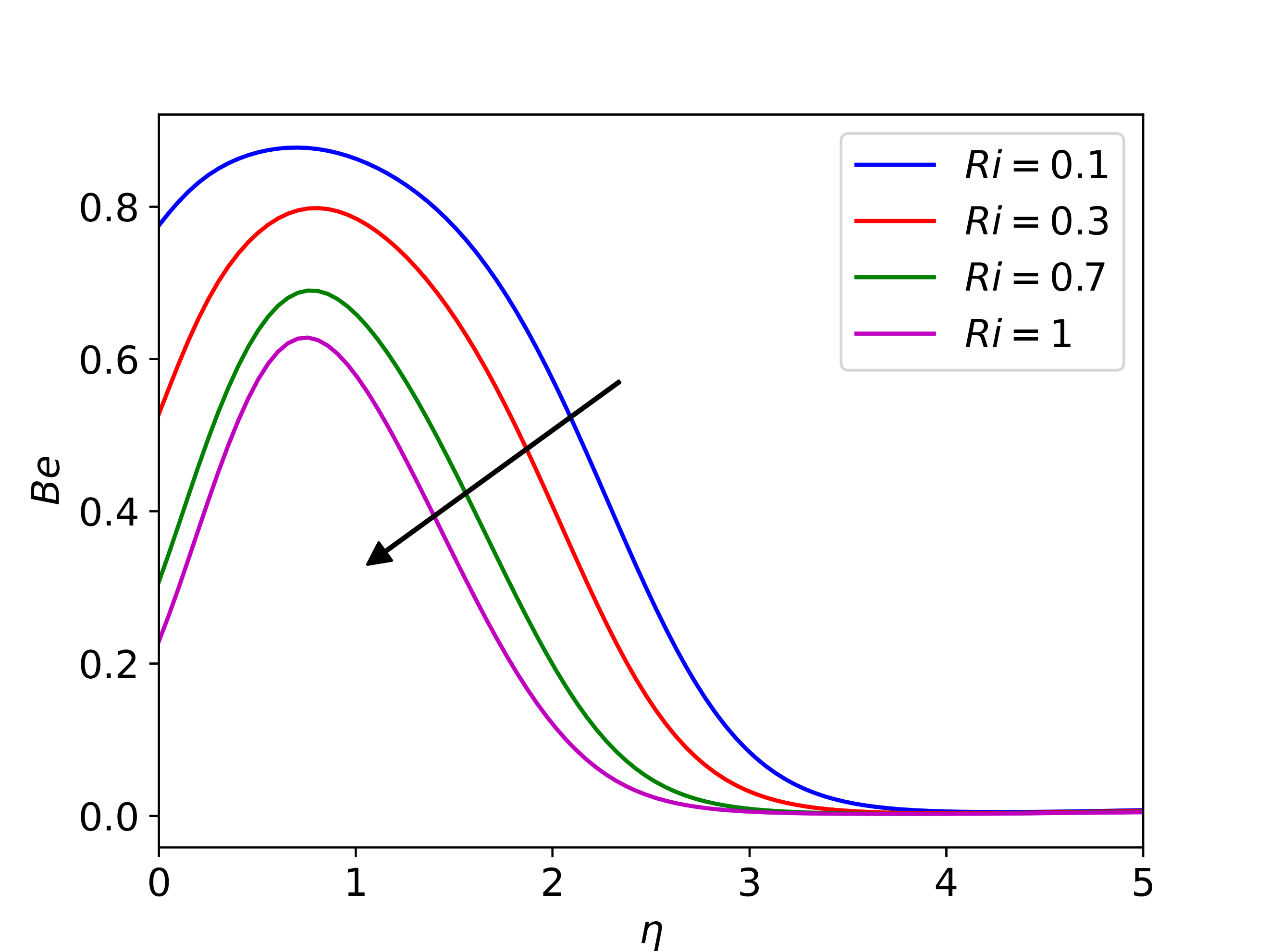


**FIGURE 2.** Variation of profiles for different .

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**FIGURE 4.** Variation of profiles for different .



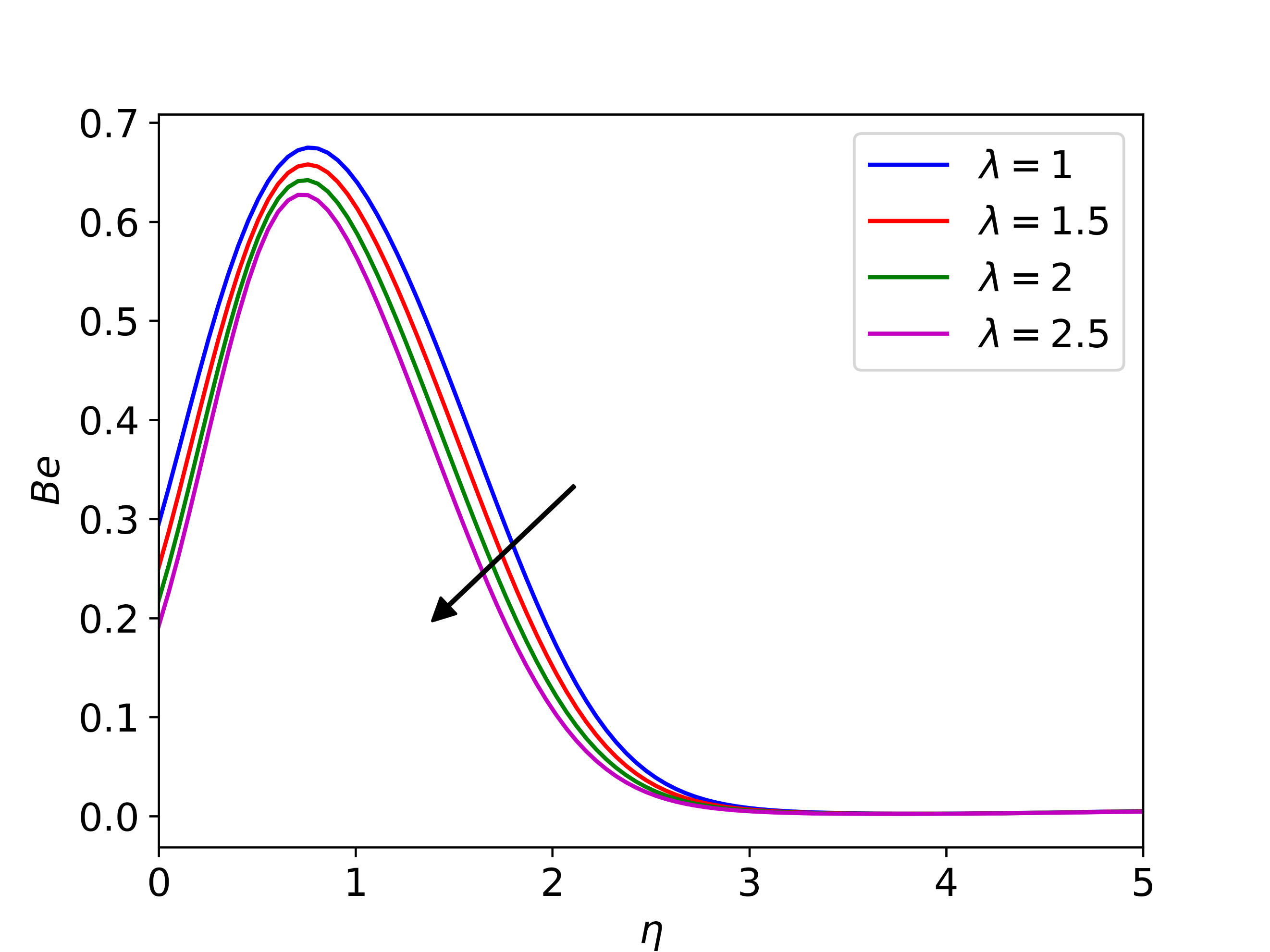
**FIGURE 5.** Variation of profiles for different .

Richardson number is associated to the buoyancy phenomenon, and results here are computed for  varying from 0.1 to 1 it means forced convection dominates. influences the in a complex way (see Fig. 4), here firstly increases with increasing near the surface while away from the surface (nearly) opposite behaviour is observed. And, decreases with growing , here in the region (nearly), maximum is observed for each value of , See Fig. 5.

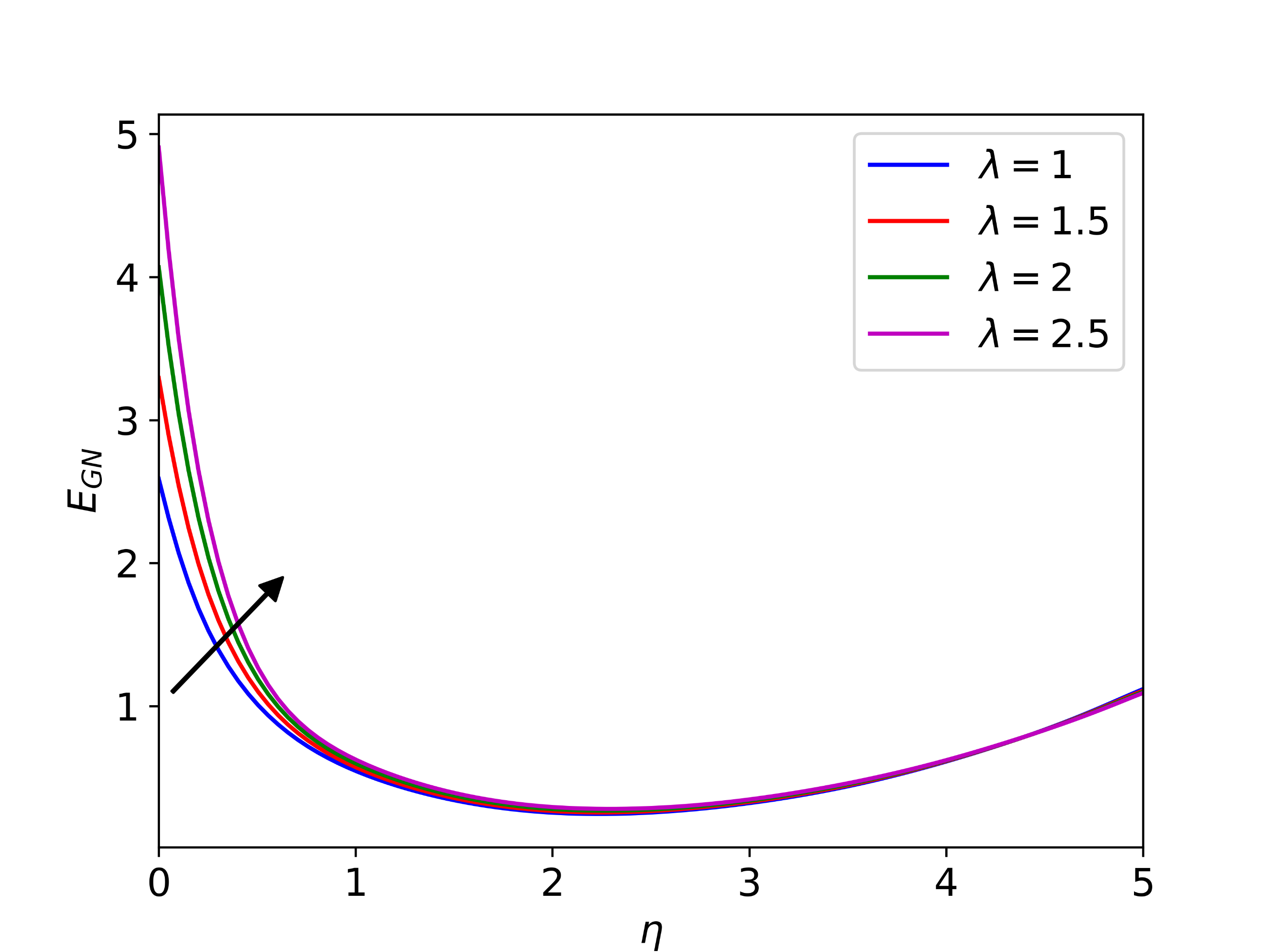
Figures 6 and 7 elucidate that increasing results in the increase in while reduces. It is worth to note that for particular , reduces with increase in and after (approximately) it starts increasing. However, the behaviour after is less significant for different values of . On the other hand, for particular , upsurges in the region and thereafter it starts reducing and it becomes constant for .

Figure 8 and 9 shows how increasing the dissipation parameter () affects the and . As effect of dissipation is directly influencing the and (see equations 10 and 12). Here increases with increase in , with maximum is observed near the surface while minimum at . On the other hand, reduces with growing , however becomes insensitive for variation in after .

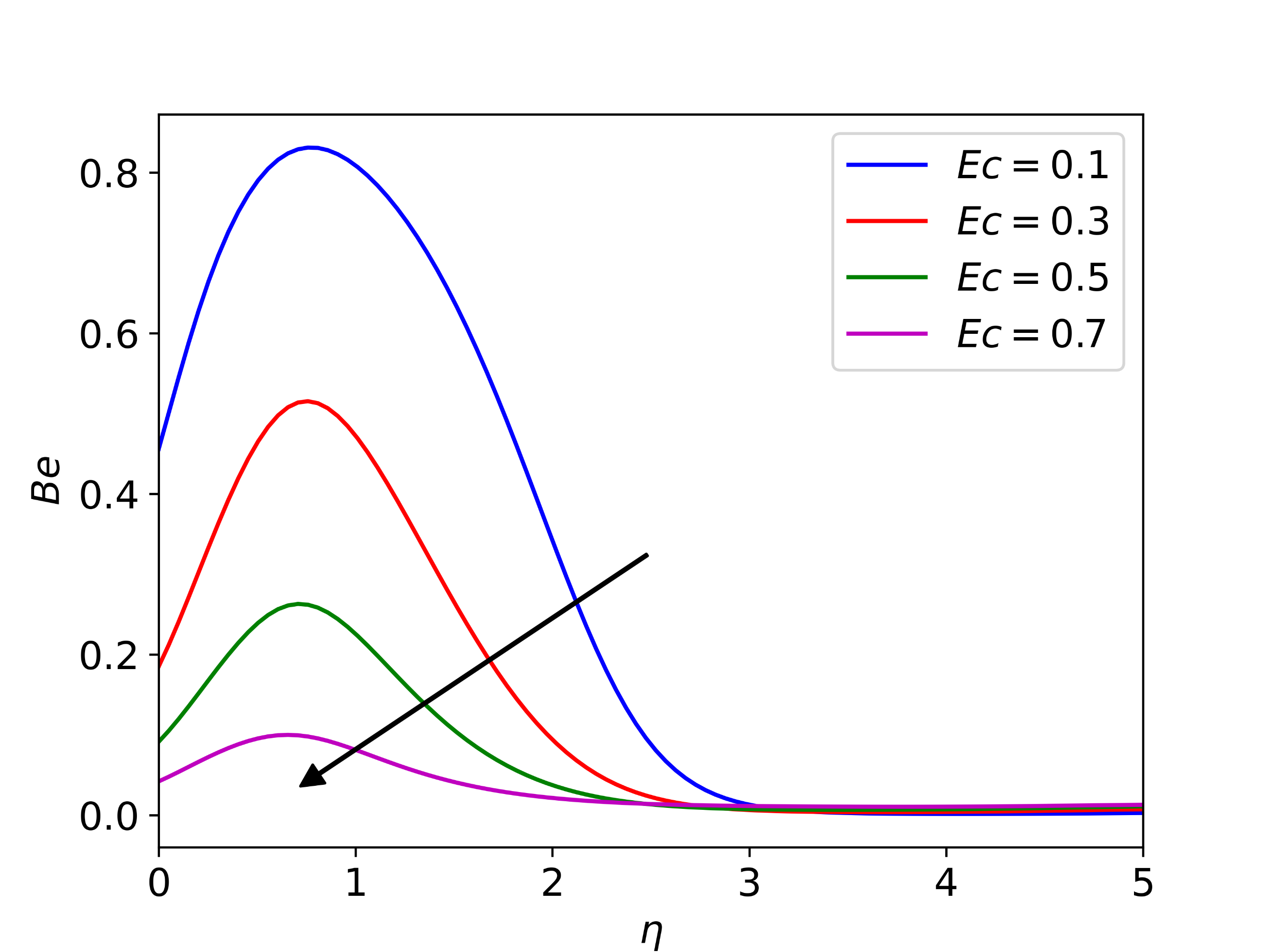
The Radiation parameter () influence both and significantly (see Figs. 10 and 11), since is directly influence with (see equation 10) and is the ratio of due to heat transfer to total . It is observed that maximum value of results in maximum in the regio while in the remaining opposite behaviour is observed, and it is worth to note that the variation in the remaining is less significant. And, shows a dual behaviour, for it decreases with growing and later it upsurges.



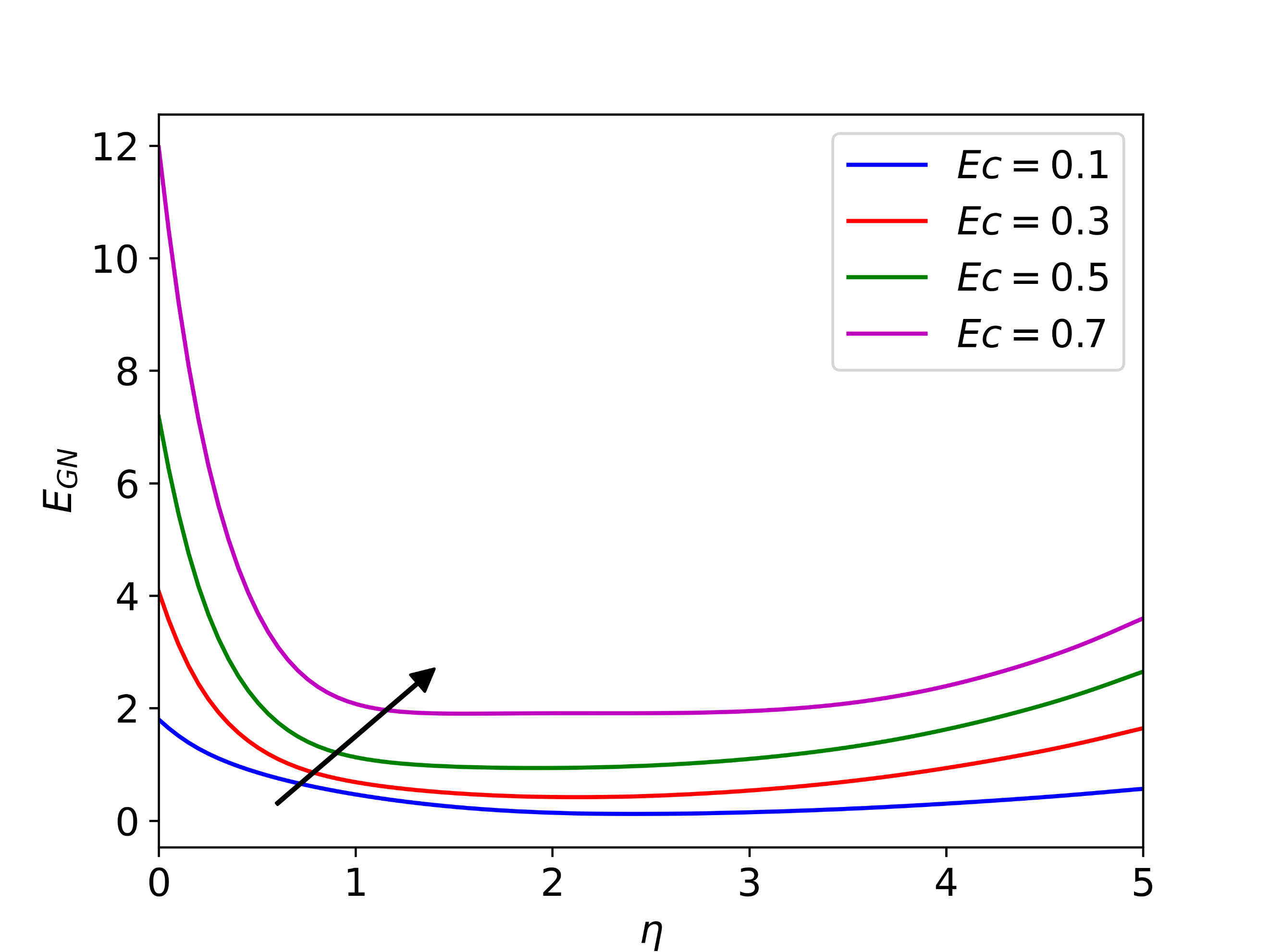
**FIGURE 7.** Variation of profiles for different .



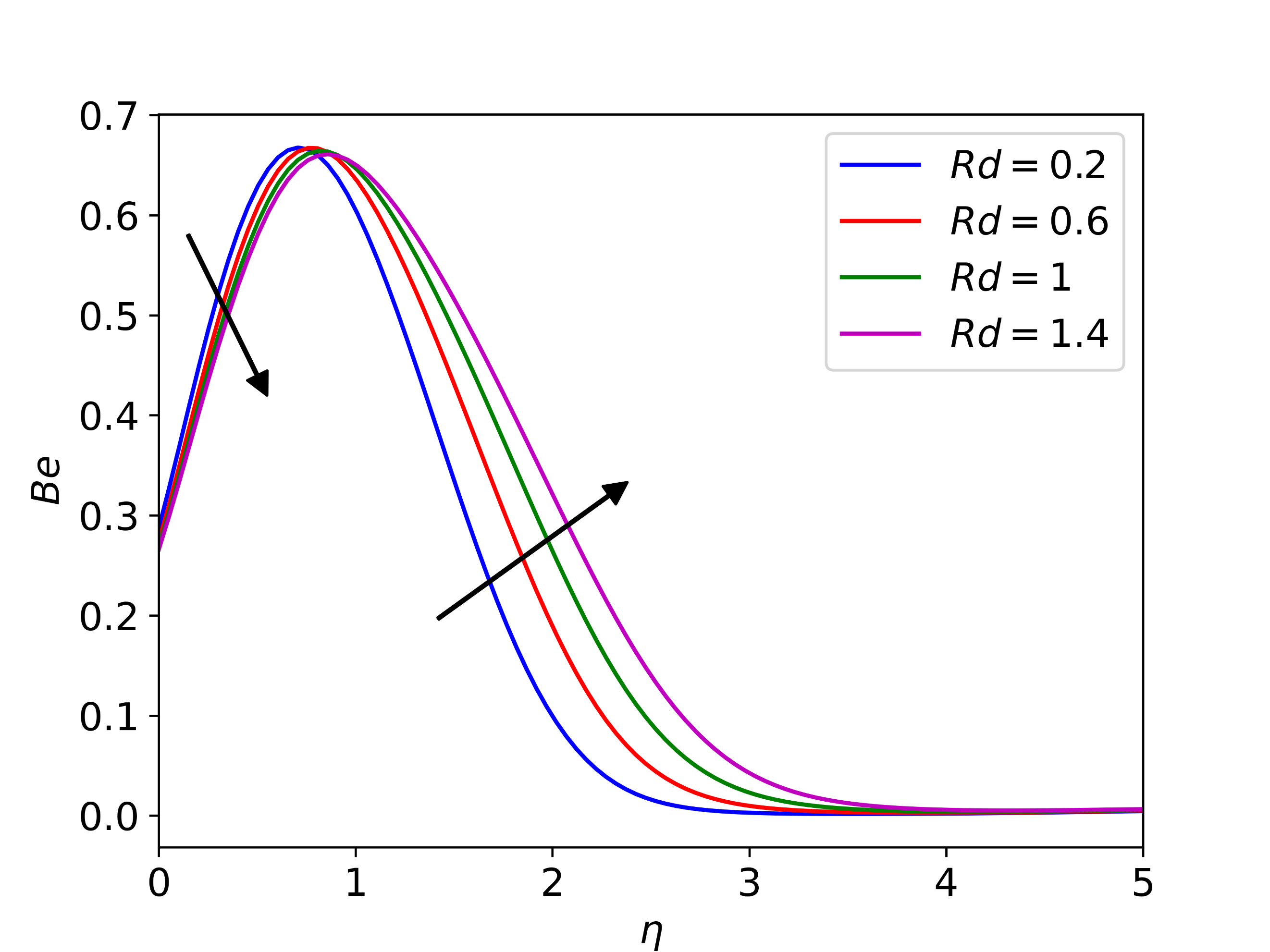
**FIGURE 6.** Variation of profiles for different .



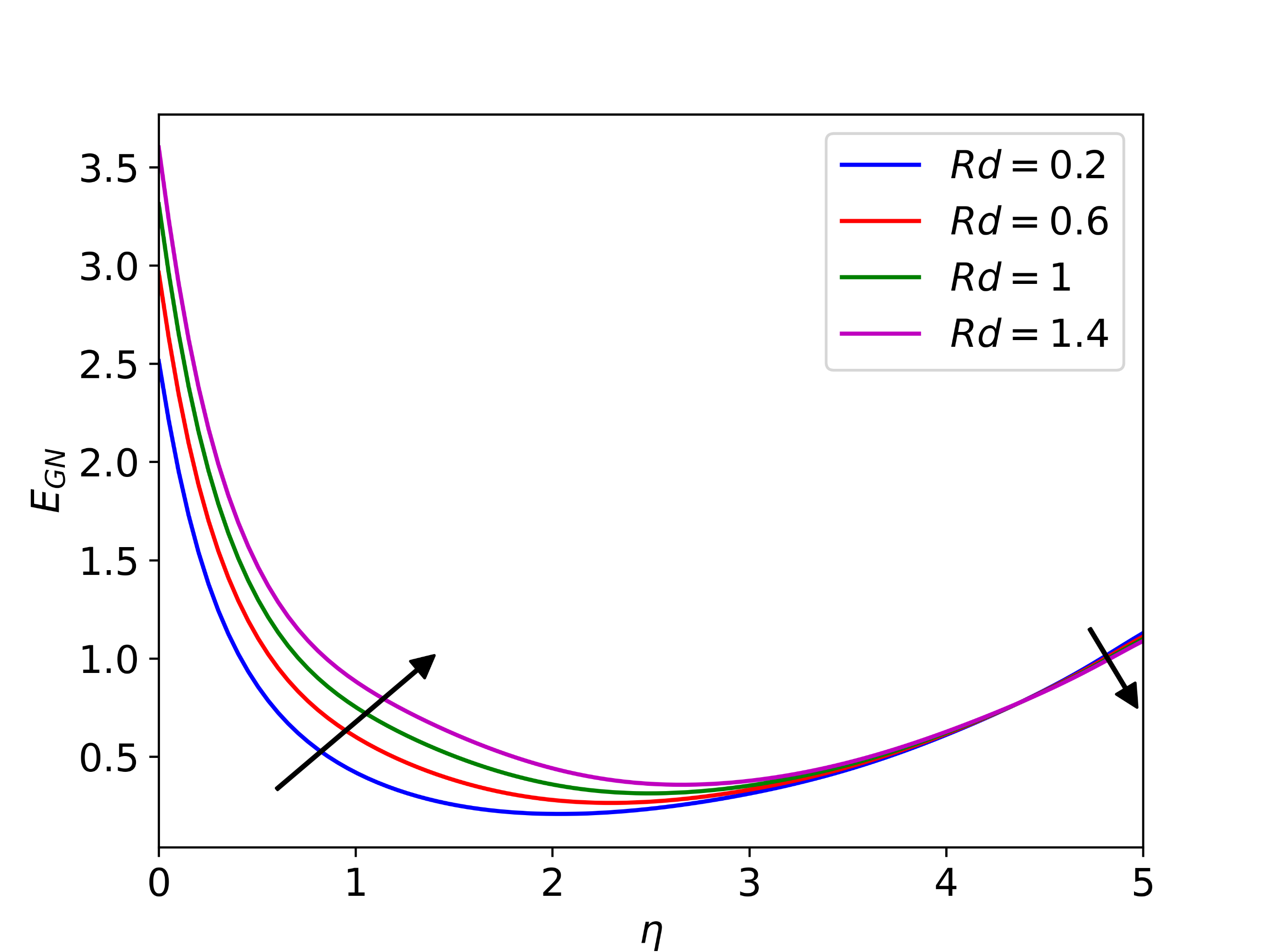
**FIGURE 9.** Variation of profiles for different .



**FIGURE 8.** Variation of profiles for different .



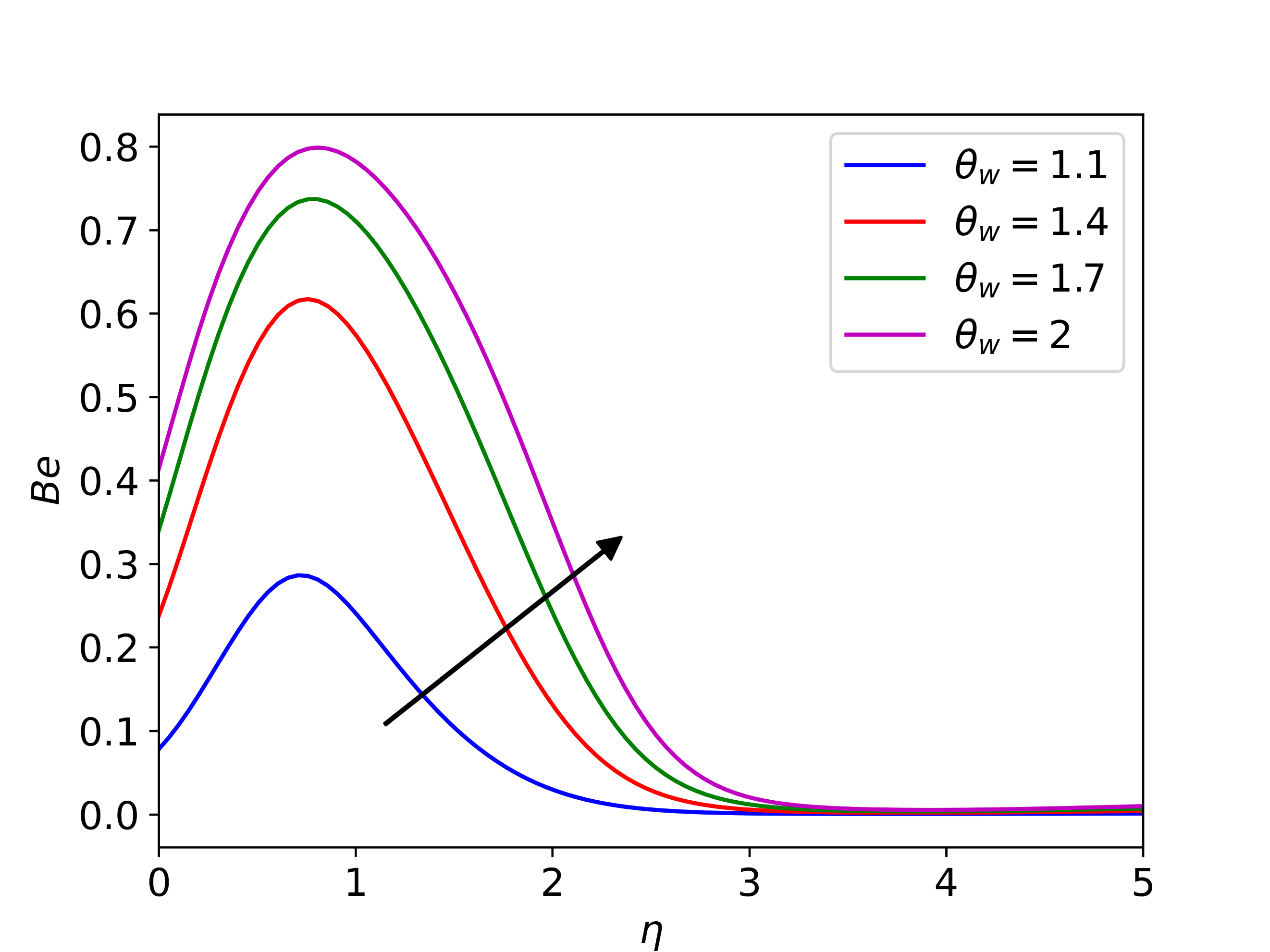
**FIGURE 11.** Variation of profiles for different .



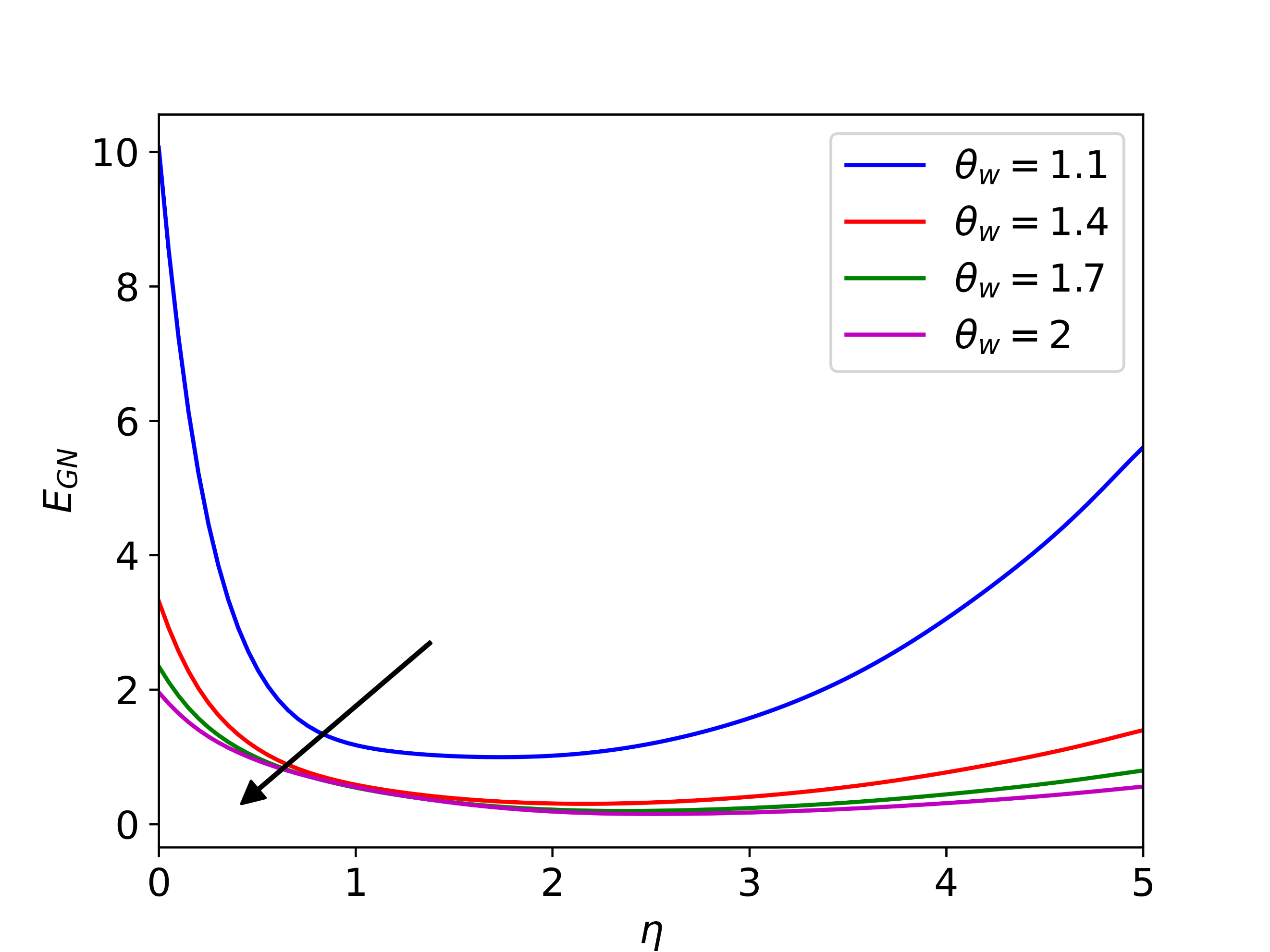
**FIGURE 10.** Variation of profiles for different .

Figure 12 and 13 shows the influence of growing on and , and is computed for growing from 1.1 to 2. Here, for growing , decreases while increases. However, for a fixed say 1.4, is maximum at than , first falls and then rises. Similar behaviour is noted for correspond to all considered values of . And for , be first increase with maximum peak at approximately and later it reduces. Here for growing , is less than 0.5, similar behaviour is noted for other values of with an observation that as grows more sudden enhancement in  is noted.

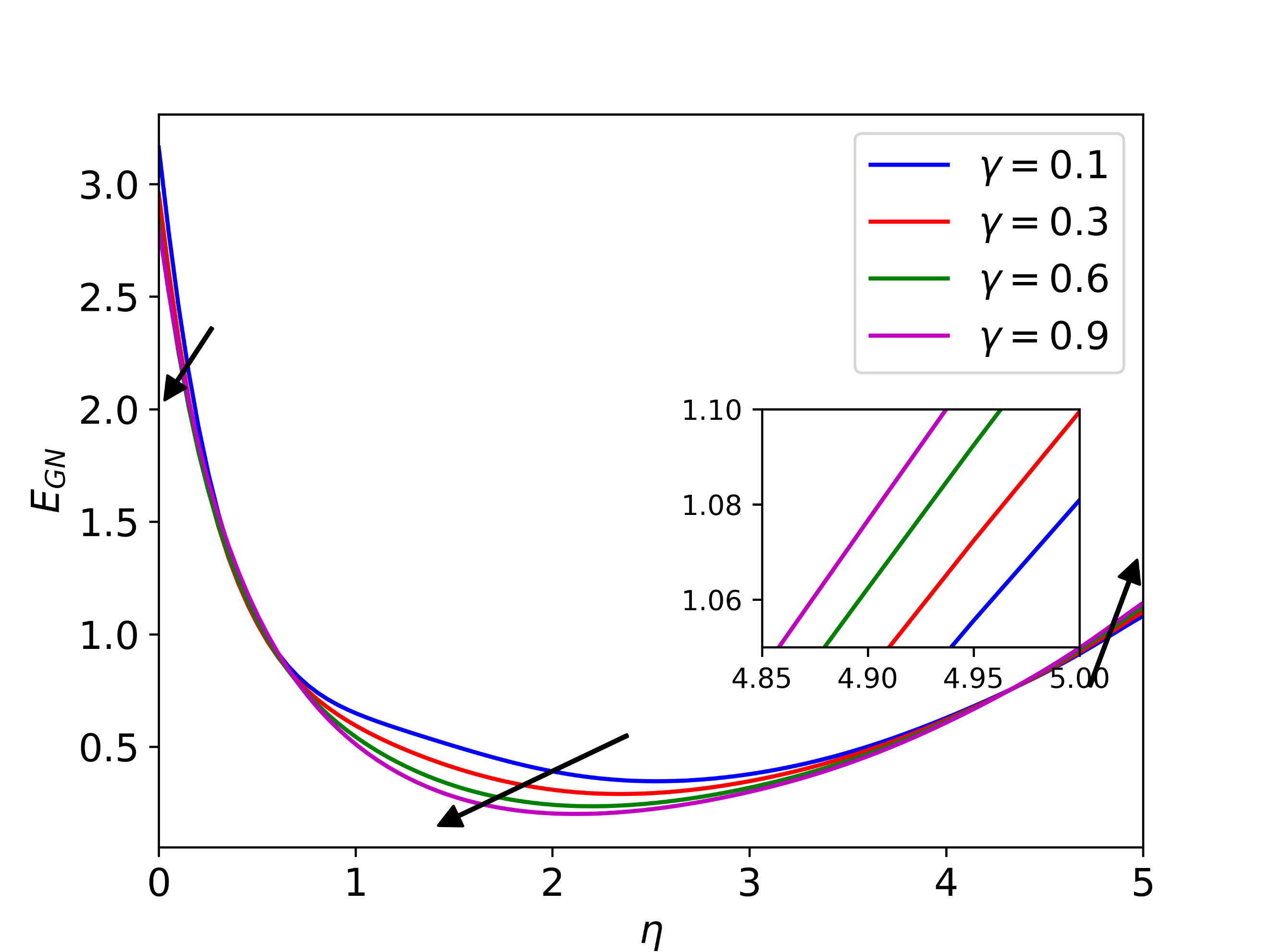
Figure 14 and 15 shows the influence of on and , as it varies from 0.1 to 0.9. Figures illustrate that increase in leads to reduction in the near the surface and later it starts increasing. On the other hand, opposite pattern is recorded for .



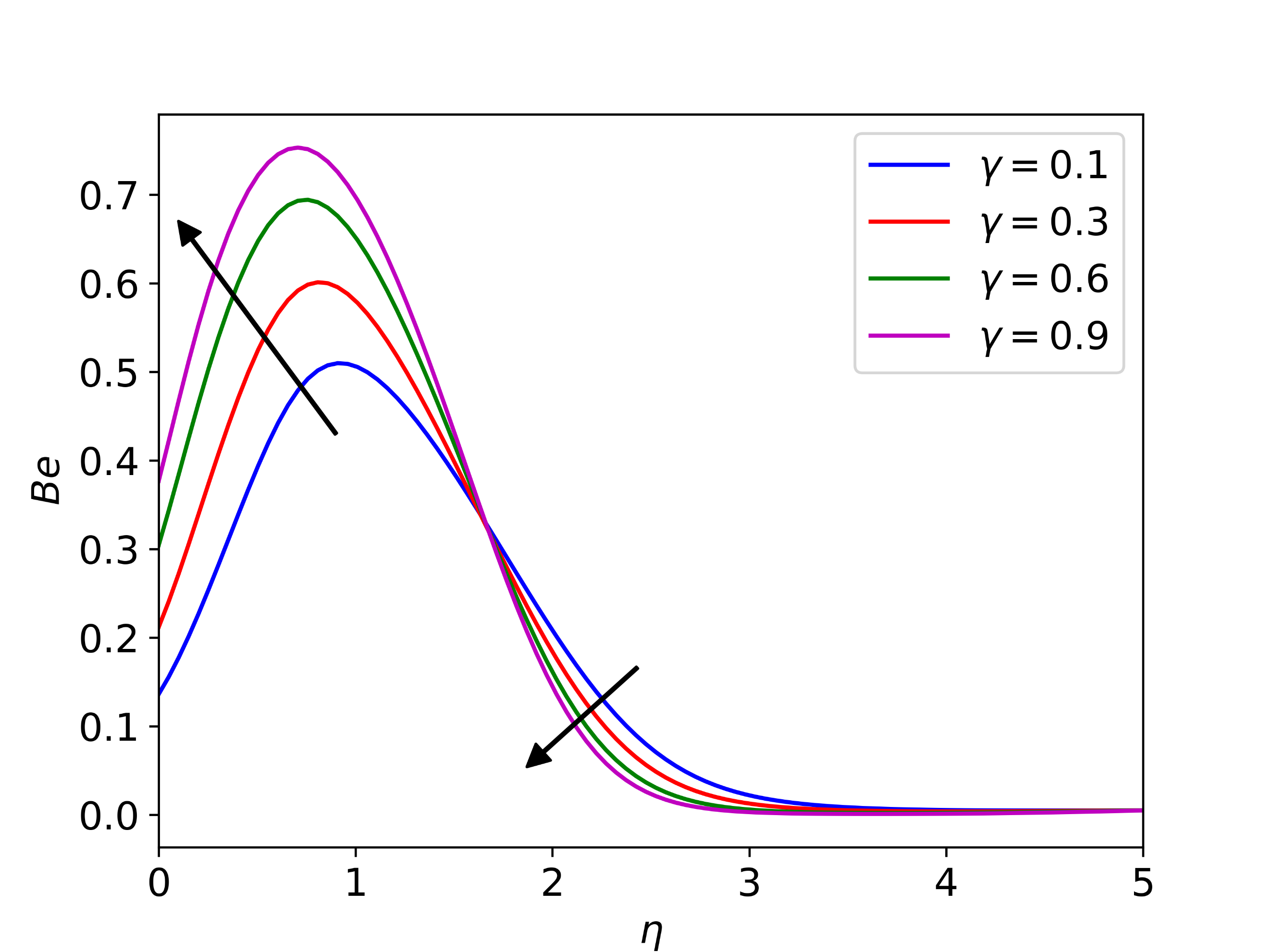
**FIGURE 13.** Variation of profiles for different .



**FIGURE 12.** Variation of profiles for different .



**FIGURE 14.** Variation of profiles for different .



**FIGURE 15.** Variation of profiles for different .

**CONCLUSIONS**

The key findings of the present study are:

* Maximum entropy generation occurs away from the surface, with magnetic field, dissipation and radiation having the strongest influence.
* Richardson number increases irreversibility near the wall but reduces it farther away, while shear-thinning and nanoparticles effects modulate thermal and viscous contributions.
* Bejan number varies non-linearly with all parameters, indicating shifting dominance between heat transfer and fluid friction irreversibility.

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