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Pressure dependent thermodynamic properties of argon plasma

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Abstract
The thermodynamic behavior of argon plasma is strongly influenced by pressure, making its study important for both fundamental research and practical applications. In this work, the dependence of key thermodynamic properties, specifically enthalpy and specific heat, on pressure is computed. Calculations are performed using the Murphy code and the results indicate a clear sensitivity of these properties to pressure variations. An increase in pressure alters the number density distribution and consequently modifies the thermodynamic characteristics of the plasma. The outcomes of this study provide useful insights for applications that require accurate control and detailed understanding of thermal plasma processes.
Keywords: *Thermodynamic properties, specific heat, enthalpy and thermal plasma*

Introduction

In recent years, thermal plasma technology has emerged as a powerful tool in a variety of industrial and scientific applications, such as waste management [1–3], synthesis of nanoparticles [4–8], arc welding [9–13], arc melting [14–16] and the separation of molten metals based on density differences [17–19]. The efficiency and reliability of these processes depend significantly on achieving consistent plasma initiation and maintaining stable operating conditions. A deeper understanding of plasma behavior is essential for optimizing such applications, which often requires detailed theoretical or computational modelling [20–26]. The accuracy of these models is largely determined by the availability of reliable plasma property data. Among these, thermodynamic and transport properties are vastly significant, as they control the distribution of energy and the transfer of momentum within the equilibrium plasma. These characteristics are strongly affected by the composition and concentration of the different species existing within the equilibrium plasma [27–29].

Pressure is a critical parameter that affects plasma equilibrium and arc dynamics [4,5,30–36]. Variations in pressure, either within the plasma core or in surrounding regions, can modify the species distribution by shifting the ionization balance. Such changes in composition lead to variations in thermodynamic properties, such as enthalpy and specific heat capacity, along with transport properties including electrical conductivity, viscosity and thermal conductivity [30,37].

In the present work, an analysis of the thermodynamic properties of argon plasma is carried out at pressures of 250 Torr, 500 Torr, and 760 Torr. These pressure conditions were selected based on their relevance to common practical applications. Many processes, such as waste management, are typically performed at atmospheric pressure (760 Torr). In contrast, reduced pressures in the range of 760 Torr to 250 Torr are widely used in applications such as nanoparticle synthesis, plasma deposition and related processes. This study aims to provide insight into the influence of pressure on plasma characteristics, which is essential for improving understanding and performance of plasma-based processes.

Method of calculation

The equilibrium composition of argon plasma at different pressures is determined by minimizing the total Gibbs free energy of the system [28,38–40]. The code includes several species, namely neutral argon (Ar), singly, doubly, triply, and quadruply ionized argon (Ar^{+}, Ar^{2+}, Ar^{3+}, Ar^{4+}), along with free electrons.

The standard-state chemical potentials of both neutral and positively charged species are evaluated using internal partition functions. These functions are constructed from electronic energy levels available in Moore's data and thermochemical information from the JANAF tables [41]. Depending on the temperature range, interactions between neutral–neutral, neutral–charged, and charged–charged species are considered. At higher temperatures (T > 5000 K), the chemical potential is mainly determined from partition functions based on the internal energy levels of the respective plasma species. Using the calculated equilibrium composition, thermodynamic properties are evaluated as proposed by A. B. Murphy, implemented through the code [39].

Results and discussion

Figures 1(a-c) illustrate the dependence of argon plasma species number density on temperature at pressures ranging from 250 to 760 Torr. For all pressures; with rising temperature, the density of neutral argon atoms (N(Ar)/V) declines, whereas the concentration of ionized species grows as a result of successive ionization processes. Consequently, the number density of electrons (n_e) changes significantly spanning approximately ten orders of magnitude between 4000 K and around 10,000 K and then attained constant value above 15,000 K. At temperatures below 10,000 K, the contributions of higher ionization states such as Ar^{2+} and Ar^{3+} are negligible. However, beyond this temperature range, these species become increasingly important and must be included in the analysis. A sharp rise in electron number density is also observed, corresponding to successive ionization processes.

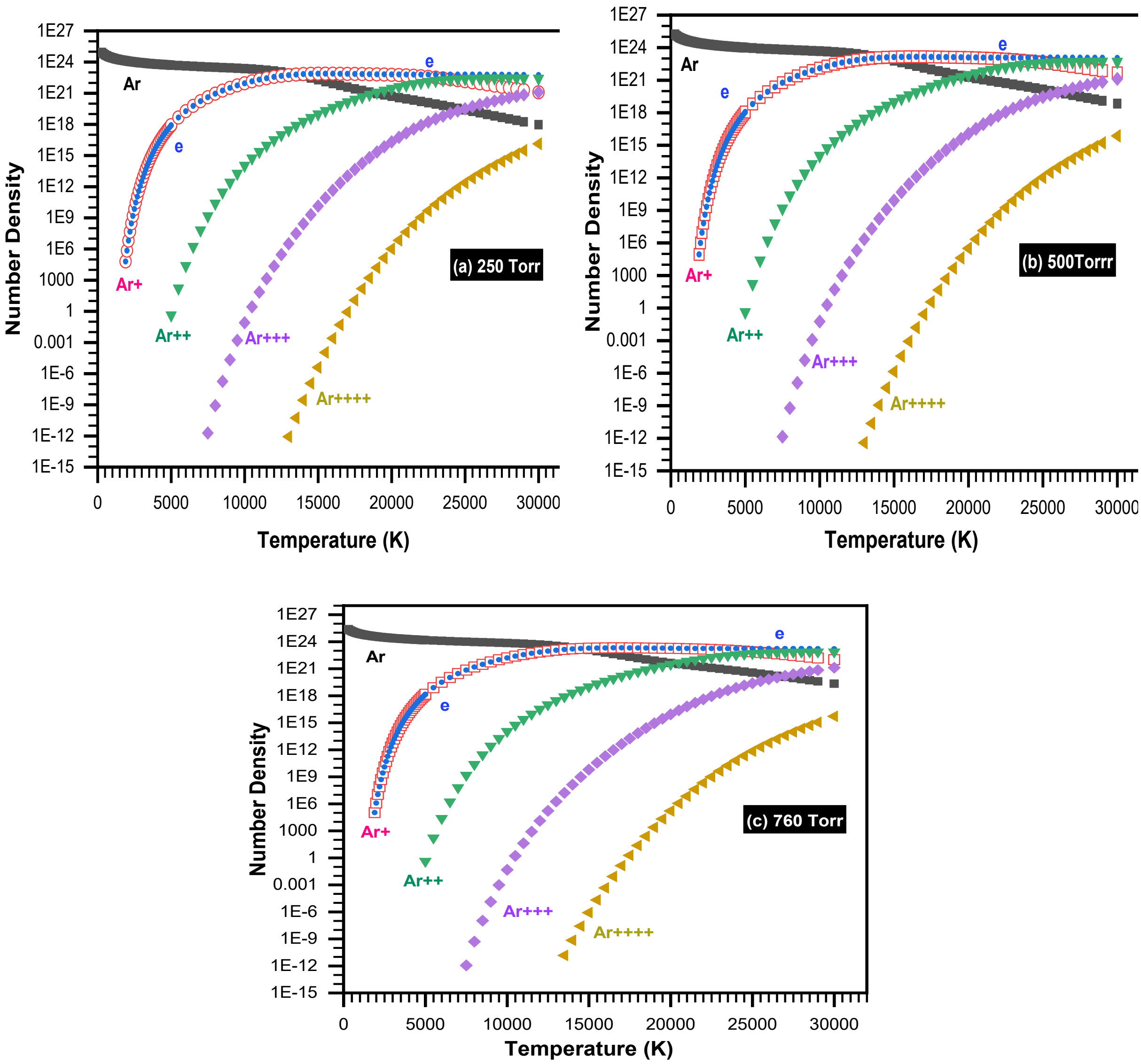

Figure 1: Equilibrium composition of Ar plasma (a) at 250 T; (b) 500 T and (c) at 760 T

To analyze the effect of pressure on species distribution, the number densities of Ar^{+}, Ar^{2+}, and $Ar3^{+}$ are presented separately in Figure 2. The results show that the first ionization stage of argon is dominant in the temperature range of 9000–20000 K, while the second ionization becomes significant at temperatures above 20000 K. The contribution of higher ionization states, particularly Ar^{3+}, remains comparatively small within the considered temperature ranges for computation. It is also observed that increasing pressure leads to higher number densities of ionized species. This behavior is attributed to the enhanced collision probabilities at elevated pressures, which promotes ionization processes [38,42–46].

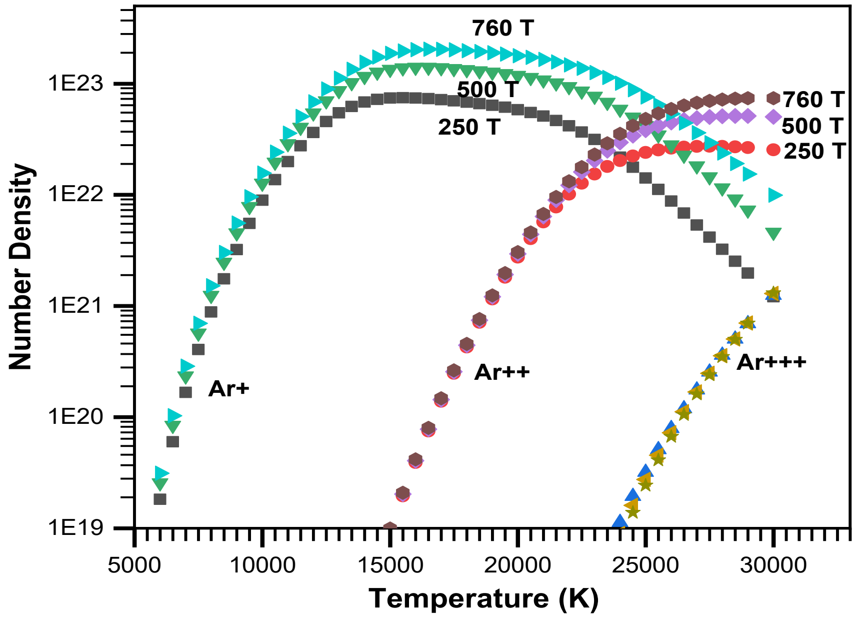

Figure 2: Effect of pressure on number density of Ar+, Ar++, Ar+++ for Ar Plasma

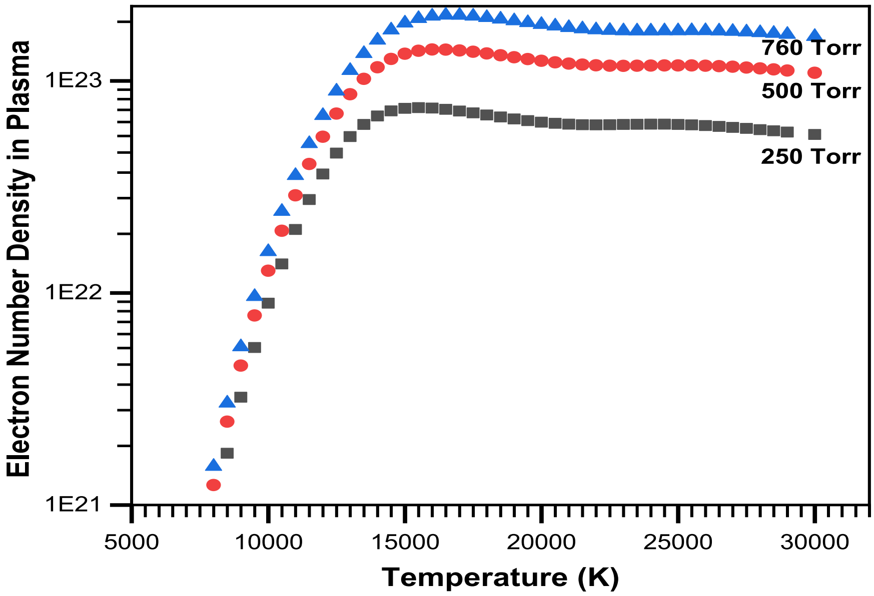

Figure 3: Effect of pressure on electron number density of argon plasma

An increase in pressure enhances the concentration of ionized particles, which in turn leads to a higher electron density. For this reason, the dependence of electron number density on temperature at various pressures is presented again separately in Figure 3. The electron density rises sharply until nearly 15,000 K; however, at higher temperatures, the rate of increase becomes much smaller and approaches a steady behavior because of intensified interactions among charged species. Previous studies have also indicated that interactions between charged particles significantly affect both thermodynamic behaviour and transport properties [11,26,28,38,40,43–45,47–52]. The results show only a slight increase in electron number density with temperature at higher values. Although the changes are small, they can still influence arc stability because higher electron density leads to increased electrical conductivity in the plasma.

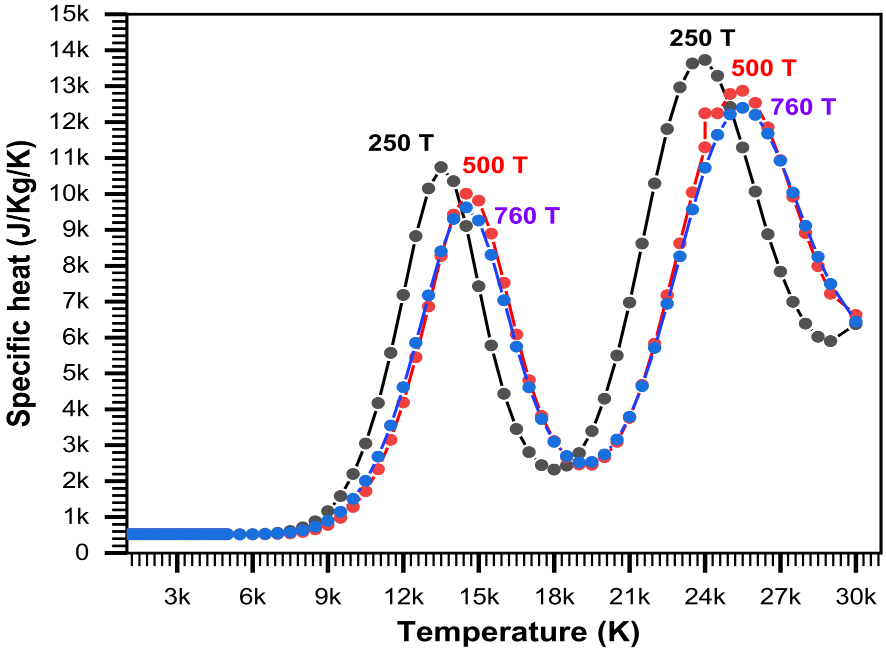

Figure 4: Effect of pressure on Specific heat of argon plasma

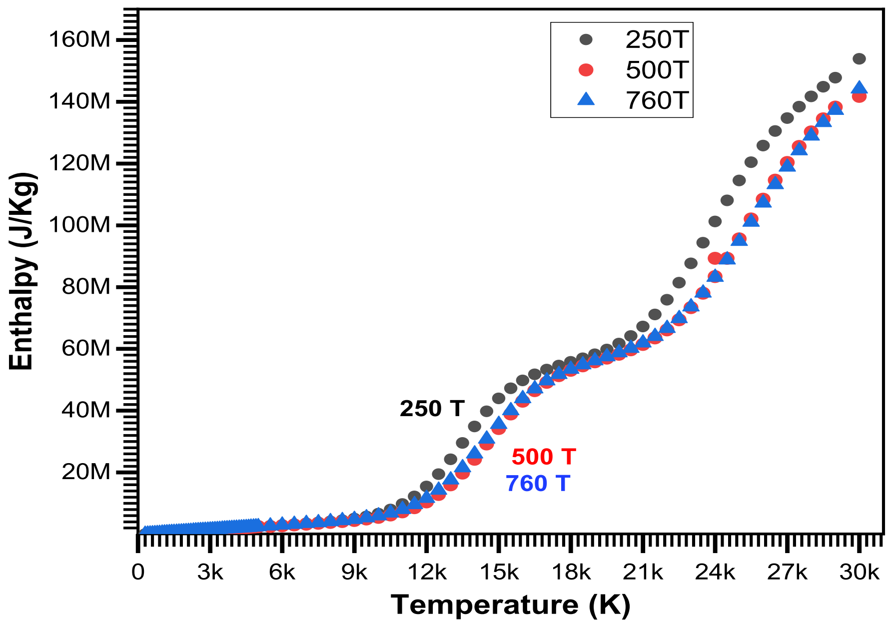

Figure 5: Effect of pressure on enthalpy of argon plasma

Figure 4 presents the variation of specific heat with temperature at different pressures via 250 Torr to 760 Torr. The first peak appears at around 6000 K, where the specific heat reaches approximately 10 kJ/kg•K. This is followed by a decrease to about 2 kJ/kg•K due to the recombination or higher ionization of Ar^{+} species. At elevated temperatures, a peak appears around 25,000 K that corresponds to the successive ionization and recombination stages of argon.

The results clearly show that a decrease in pressure leads to an increase in specific heat, and the corresponding peaks shift toward lower temperatures. This behavior indicates that pressure has a strong influence on specific heat, which depends on the distribution of species present at a given temperature. Lower pressure conditions shift ionization phenomena to lower temperature regions and increase the maximum specific heat values. Figure 5 shows the variation of enthalpy with temperature at different pressures. As expected, enthalpy increases with temperature for all cases. The results are consistent with published literature. At 250 Torr, enthalpy values are higher and the peak shifts toward lower temperatures. In contrast, at 500 Torr and 760 Torr, the changes in enthalpy are relatively small, which can be attributed to stronger interactions among charged-charged particles at higher pressures. Thus, even small changes in plasma composition caused by pressure variation can significantly affect the thermodynamic properties of Ar plasma. Therefore, keeping the operating pressure steady is crucial for maintaining arc stability and effective process control.

Conclusion

The results show that pressure has a relatively small influence on the equilibrium composition of argon plasma, but its influence on thermodynamic properties is more pronounced. A decrease in pressure shifts ionization processes toward lower temperatures, resulting in changes in the species distribution within the plasma. Consequently, both specific heat and enthalpy increase, and their characteristic peaks move toward lower temperature regions at 250 Torr. While is almost independent at 500-760 Torr.

These findings emphasize the importance of considering pressure effects in plasma processes. Even small variations in plasma composition due to pressure changes can significantly affect its thermodynamic behavior. Therefore, maintaining stable operating pressure is essential for achieving consistent plasma performance and arc stability in various plasma-based applications.

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Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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