Nonadiabatic and Frictional Constant Area Duct Flow: A Visual Software Based Simulation For Compressible Systems

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ABSTRACT: Numerical investigation of compressible flows in constant area ducts becomes substantially complicated when the surface roughness and heat flux conditions simultaneously act as independent and considerable boundary conditions that create significant influences on the flow and heat transfer characteristics. This article presents GAS-DYN v2.0, a specialized software package, capable of handling nonadiabatic and frictional systems with the contribution of a database, developed also by the author, which involves the real time temperature-dependent gas properties. Results of the presented computational analysis are in harmony with the available literature, which not only indicates the reliability of the package but also points out its adaptability to MSc and PhD level research studies and for the compressible flow system design projects.

Keywords: nonadiabatic; frictional; compressible flow; constant area duct; GAS-DYN v2.0

INTRODUCTION

Compressible flows and gas dynamics problems constitutes a wide variety of applications such as aerodynamic design of jet planes and rockets, aero gas turbine engines and gas carrying ducts of pneumatic systems. The main principles and the available computational methods [1] are developed either for isentropic cases or for typical shock regimes, where the both are considered to be adiabatic and frictionless. However the numeric solution procedure becomes considerably complex when the surface friction and heat transfer conditions play a remarkable role on the overall assembly performance. There have been many numerical and experimental studies in compressible systems considering the nonsentropic character and irreversibilities. Lear et al. [2] presented
a model to describe the gas dynamics analysis with inter-phase heat transfer and slip, where the exit kinetic energy and system efficiency were the main considerations. The recent experimental data of a developing jet engine were demonstrated by Sato et al. [3], who determined the smaller diameter ducts to improve both heat transfer performance and system compactness. As the cooling effects on compressible gas dynamics were experimentally investigated by Back et al. [4], Ahmad [5] carried out computational fluid dynamics investigations to compute effective discharge coefficient of compressible flow in the presence of surface heat flux conditions; where the heat transfer analysis were performed with Dittus–Boelter equation and the computed discharge coefficient values were within 0.88—9.97. Bartz [6] considered the heat transfer phenomena in compressible flows and considered Nusselt number as a function of inlet stagnation pressure. Ribault and Friedrich [7] numerically handled compressible boundary layers both along adiabatic walls at different Mach numbers and along cooled walls at hypersonic speeds. Effects of the inlet stagnation pressure to back pressure ratio on system discharge coefficient were experimentally studied by Park et al. [8], where the discharge coefficients were recorded to drop from 1 to 0.65 for pressure ratios below 1.25. Moreover Paik et al. [9] correlated discharge coefficient with Reynolds number and determined the discharge coefficient to increase with Reynolds number, thus in systems with higher mass flow rates.

Due to complexity of the typical engineering-scientific topics, many of the basic scientific principles need to be considered simultaneously, which makes it impossible to tackle them with traditional methods. Improvements in computer/software science and technology, lead researchers to benefit from the visual-computational utilities that are accepted to be of fast and reliable nature. In the digital technology age, the computer aid is becoming a widespread tradition, regardless of the fact that the research matter is either of single or interdisciplinary type. Ozalp [10] investigated the steady and transient performance of gas turbine engines by a visual software and supported the execution process by two databases: the first one for the real time compressor and turbine map data of existing gas turbine engines, the second one for the available gas turbine fuels. Ozalp and Ozel [11] developed an interactive software package, a specialized tool for hydrodynamic-slider bearing-lubrication, which is capable of performing temperature-dependent viscosity runs on various pad geometries and boundary conditions. Sanz et al. [12] developed an antenna module, which not only includes topics on radiation, transmission equation, basic types of antennas, and antenna arrays, but also incorporates a highly interactive environment, virtual labs, and simulation software. Valocchi and Werth [13] proposed six different models to explore coupled processes such as advection, longitudinal and transverse dispersion, linear and rate limited sorption, and first order decay, and integrated these items within a web-based environment to simulate groundwater pollutant fate and transport. Lopes [14] described a user-friendly software for the calculation of general piping system networks composed of virtually any parallel and series pipe arrangement, where the solution of the network is made with recourse to the iterative method of Hardy Cross.

For compressible-constant area duct flows, simultaneous handling of surface roughness and heat transfer conditions is a challenging task and requires further investigation. Ozalp [15] presented GAS-DYN, a visual software package for isentropic nozzle flows; however, issues requiring additional study include the combined effects of nonadiabatic and frictional character to provide a deeper understanding on the mechanisms of nonisentropic structure. This paper introduces the recent version of the package, entitled GAS-DYN v2.0, which is developed to investigate the nonisentropic, compressible flows in constant area ducts. The software is supported by a fluid database, including the gas property variations with flow temperature, and equipped with the available heat transfer approaches and with various numerical marching techniques.

**GOVERNING EQUATIONS**

The calculations rely on the principles of mass and energy conservation and on the momentum and state equations applied to the control volume, given in Figure 1, and the main aim is to develop an efficient model capable of handling surface roughness and constant heat flux conditions simultaneously. It is
assumed that the stagnation conditions of pressure \( (P_0) \) and temperature \( (T_0) \) in the storage tank, upstream of the duct, are homogeneous and, as in many numerical work [2,8], the air velocity \( (U) \), Mach number \( (M) \), static pressure \( (P) \), and temperature \( (T) \) are considered to be uniform across any section normal to the flow axis.

Since air properties, like specific heat at constant pressure \( (C_p) \), kinematic viscosity \( (\nu) \), conduction heat transfer coefficient \( (k) \), and Prandtl number \( (Pr) \), are substantially dependent on temperature [16], they are characterized by sixth order polynomials with an uncertainty of less than 0.02% and the temperature dependency is indicated by the superscript \( T \) throughout the formulation. As the work is interested in flows with friction and heat transfer, stagnation properties will also vary in the flow direction, thus the conventional equations (Eq. 1a,b) for compressible, isentropic, and one-dimensional flows are applicable only with the simultaneous handling of the momentum and energy equations.

\[
\frac{(P_0)_i}{P_i} = \left(1 + \gamma - \frac{1}{2} M_i^2 \right)^{T_i - T_0} = 1 + \frac{\gamma - 1}{2} M_i^2 \\
\frac{(T_0)_i}{T_i} = \left(1 + \frac{\gamma - 1}{2} M_i^2 \right)^{\frac{1}{T_i}} = 1 + \frac{\gamma - 1}{2} M_i^2
\]

(1a–b)

The nodal values (subscript \( i \)) of air velocity, density \( (\rho) \), and mass flow rate \( (m) \) can be calculated by Eqs. 2a–c, where \( m \) being the most significant consideration from numerical point of view, is kept constant in the flow direction. On the other hand, Reynolds number (Eq. 2d) is assigned to each differential cell (subscript \( n \)) with the mean cellular values of \( U, D \), and \( \nu \),

\[
U_i = M_i \sqrt{\gamma RT_i} \quad \rho_i = \frac{P_i}{RT_i} \\
m = \rho_i U_i A \\
\frac{m}{\rho_i} = \frac{U_i D}{\nu_i}
\]

(2a–d)

where \( D \) and \( A \) stand for diameter and cross sectional area of the duct and \( \gamma \) and \( R \) for specific heat ratio and gas constant of air. The friction coefficient \( (f) \) is a function of both \( Re_D \) and surface roughness \( (\varepsilon) \) (Eq. 3a) [16], and the cell-based shear stress \( (\tau) \) and friction force \( (F_f) \) can be expressed with Eqs 3b,c.

\[
\frac{1}{\sqrt{f_n}} = -3.6 \log \left[ \frac{6.9}{(Re_D)_n} + \left(\frac{\varepsilon/D_n}{3.7}\right)^{1.11} \right] \\
\tau_n = \frac{f_n}{\rho_n} \left( \frac{U_n}{2} \right)^2 \quad (F_f)_n = \tau_n \pi D_n A x_n
\]

(3a–c)

The one-dimensional momentum (Eq. 4) and energy equations (Eq. 5a) are applied to each differential cell in the duct, where the nodal properties such as \( P, U, \) and \( C_p \) are interrelated with the contributions of cellular variants like \( F_f \), impulse \( (I) \), and cellular heat flux \( (dq) \). Equation 5a represents conservation of mechanical and thermal energy by the implementation of cell-based surface flux (Eq. 5b) and the frictional loss term,

\[
P_i A_i + m U_i = P_{i+1} A_{i+1} + m U_{i+1} + (F_f)_i + I_i \\
(C_p)_i T_i + \frac{U_i^2}{2} + (dq)_i = (C_p)_{i+1} T_{i+1} + \frac{U_{i+1}^2}{2} + (F_f)_{i+1} \frac{U_{i+1}}{2} + (dq)_{i+1} = \frac{Q(A)_n}{m}
\]

(4)

where \( Q \) defines the surface heat flux. The nodal values of Nusselt number \( (Nu_D) \) and convective heat transfer coefficient \( (h) \) are calculated by Dittus–Boelter Equation [16] (Eq. 6a) for heating \( (\zeta = 0.4) \), moreover the combined effects of \( \varepsilon \) and \( Q \) on \( m \) are investigated through the nondimensional discharge coefficient \( (C_d) \) of Eq. 6b, which compares the real \( m \) with that of the isentropic case.

\[
(Nu_D)_n = \frac{h_n D}{k_n} = 0.023 (Re_D)_n^{0.8} P^0.5 \quad C_d = \frac{m_{real}}{m_{isent}}
\]

(6a–b)

Figure 2 Hierarchical structure of “GAS-DYN v2.0.”
COMPUTER IMPLEMENTATION: GAS-DYN v2.0

Due to the iterative character of the computational background, GAS-DYN v2.0 should be run with a P- IV processor PC, which is equipped with at least 512 Mbyte RAM, to be able to store the above defined complete set of fluid and flow data for up to 25,000 sequential cells [17], which can vary according to the users’ demand. As the programming domain of the package is selected as Visual Basic 6.0 [18], the interactive menus are developed to fit a 1,024 × 768 resolution, which provides the outmost interrelated viewing for each purpose. The programming logic of the package is based on six distinct, but also dependent, “Operational Platforms” (OP) that incorporate to generate the reliable chain of file-input-database-iteration-run-plot operations.

Figure 3 Interactive menus of “GAS-DYN v2.0”: (a) Main Menu, (b) Duct Configuration, (c) Inlet-Exit Data, (d) Available Gases, (e) Heat Transfer Approaches, (f) Marching Technique.
As given in Figure 2, the hierarchical structure contains the complete set of items that these OP need to function in harmony. Upon start-up, the “Main Menu” appears at the first hand, displaying the main headings, like ‘‘Initiate Operation, Project Types, Input Data, Specific Determinations, Accomplish,” and the corresponding command buttons (Fig. 3a). To guide the users, the “Main Menu” is designed in the operation order, so that each subsequent main heading appears only after the execution of the preceding one. File operations are coordinated by the first OP; using the command buttons of the ‘‘Initiate Operation” heading, “New Project,” “Save Results,” “Open Results,” and “Exit” activities can be performed.

The second OP, charged with the configuration of the complete input procedure, is executed through the headings of ‘‘Project Types” and ‘‘Input Data.” “Ideal Flow,” “Flow with Friction,” “Flow with Heat Transfer,” and “Flow with Friction and Heat Transfer” are the four available run modes that are sufficient to meet both the fluid mechanics and heat transfer needs of the governing theory. As the duct length and diameter are given by the command of “Geometric Data,” the surface and heat transfer definitions of the duct are supplied in the “Duct Configuration” (Fig. 3b). The input screen (Fig. 3c) for the specific properties at the inlet and exit includes the \((T_0)_{in}, (P_0)_{in}, \) and \(P_b\) values of the system and performed with the command button of “Inlet-Exit Data.” The flowing gas is selected from a set of nine alternatives, including Air, Ammonia, Carbon Dioxide, Carbon Monoxide, Helium. In addition to the molecular weight and gas constant values, the temperature-dependent properties like \(\nu, C_p, k, \) and \(Pr\) are also read from the pre-created database, with the cooperation of the second (input) and third (database) OPs. The raw data [16], as given in Figure 3(d), are read from the fluid-database and are processed within the curve fitting subroutine of the input OP to turn the temperature dependency of each fluid property into a definable nature with sixth order polynomials as defined in the “Governing Equations” section. The fourth OP for the iteration procedure works under the heading of ‘‘Specific Determinations,” where the “Heat Transfer Handling” and “Marching Technique” commands presents the four available heat transfer approaches (Fig. 3e) and the methods for temperature-dependent fluid property handling (Fig. 3f) respectively. As the geometric definition, the thermodynamic inlet/exit, and surface-heat transfer definitions are completed, the fifth OP can be activated by the “Run” command. Since the solution procedure depends highly on the selected options of iteration procedure, the fourth and fifth OPs work in coordination at each node and at each iteration step. GAS-DYN v2.0 performs a mapping operation, for the complete flow volume and the nodal results like Mach number, density, stagnation/static temperature and pressure, and the cellular outputs of friction force and heat transfer coefficient are stored in an array. The plot applications of GAS-DYN v2.0 are organized by the sixth OP and can be accessed by the “Plots” command button of Figure 3(a). The grid sensitivity of up to 25,000 equally spaced cells confirms the quality of the output plots, where the above-mentioned stagnation and static fluid parameters can be investigated by not only on streamwise variation basis but also with respect to each other. Moreover, to manage the cooperation of the six OPs and to organize the visual—interface interactions, a special subprogram, named as “Execution Controller” (EC) [10,11], is also assembled to the package. EC behaves as the main body of the complete structure, organizes the operation order of the OPs and can deliver any kind of numerical/executional information, on request, at run time of a continuing project.

**Computational Analysis**

To put forth the computational capabilities of GAS-DYN v2.0 and to interpret the combined influences of inlet stagnation pressure, surface roughness, and heat flux conditions on flow and heat transfer characteristics of compressible constant area duct flows, several scenarios are investigated. Throughout the computations the \((T_0)_{in}, P_b, D, \) and \(L\) are fixed to 400 K, 100 kPa, 0.4 m, and 0.5 m respectively, however to produce a comprehensive overview, numerical investigations are carried out with \((P_0)_{in} = 101, 150, \) and \(200\) kPa, corresponding to \(\beta = (P_0)_{in}/P_b\) of 1.01, 1.5, and 2. Effects of the surface roughness on the flow and heat transfer characteristics is simulated by applying the nondimensional cases of \(\varepsilon/D = 0.0025, 0.0125, \) and \(0.025,\) moreover, the effects of constant surface heat flux are evaluated by imposing three distinct values of \(Q = 400, 1,200, \) and 2,000 kW/m². Results of the isentropic and nonadiabatic and frictional cases are discussed through the streamwise variations of Mach number, density, friction force, heat transfer coefficient, stagnation pressure, and temperature, and with discharge coefficient.

**Results and Discussion**

Variations in the streamwise \(M\) are given in terms of \(\beta\) and \(Q\) for the fixed nondimensional surface roughness
Figure 4 Influence of surface heat flux on the streamwise variations of (a) Mach number and Density ratio, (b) Friction Force and Convective Heat Transfer Coefficient.
Table 1 Combined Effects of $\beta$, $Q$ (kW/m²), and $\varepsilon/D$ on $M_{in}$

<table>
<thead>
<tr>
<th>$\varepsilon/D \ \backslash \ Q$</th>
<th>$\beta = 1.01$</th>
<th>$\beta = 1.50$</th>
<th>$\beta = 2.00$</th>
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<td>0.025</td>
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</tr>
</tbody>
</table>

Isen. Case: 0.1187 Isen. Case: 0.7727 Isen. Case: 0.9246

Table 2 Combined Effects of $\beta$, $Q$ (kW/m²), and $\varepsilon/D$ on $\rho_{in}/\rho_{ex}$

<table>
<thead>
<tr>
<th>$\varepsilon/D \ \backslash \ Q$</th>
<th>$\beta = 1.01$</th>
<th>$\beta = 1.50$</th>
<th>$\beta = 2.00$</th>
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</tr>
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</tbody>
</table>

Isen. Case: 1.00 Isen. Case: 1.01 Isen. Case: 1.06

case of $\varepsilon/D = 0.0125$ in Figure 4(a), which indicates that flows with lower $\beta$ result in lower Mach number at the inlet ($M_{in}$) and at the exit ($M_{ex}$). When compared with the $\beta = 2$ pattern, $\beta = 1.50$ caused a decrease of 16% and 14% in $M_{in}$ for the isentropic and $Q = 2,000$ kW/m² cases. In the downstream section, $M_{ex}$ values are identical and equal to 1, being independent of $M_{in}$, for the $\beta = 2$ case, since $(P_{0})_{in} = 200$ kPa corresponds to choking condition for the complete $Q$ range. However as $\beta$ is lowered, the ducts run at unchoked condition with accompanied decreases in $M_{ex}$. The variations in $M_{ex}$, when compared with the above discussions on $M_{in}$, are small and kept in the range of 2% – 4% for the complete $Q$ and $\beta$ set. Figure 4(a) further implies that application of surface heat flux produces lower $M$ values throughout the duct, regardless of the level of $\beta$. These findings are similar to those of Lear et al.’s [2] numerical and Sato et al.’s [3] experimental determinations. Application of the constant surface temperature condition on the duct wall [2] caused flow velocities, thus $M$, to decrease, whereas the cooling of the flow surface [3], which is the counter operation of the present work-focus, resulted in higher mass flow rates. When compared with the isentropic case, the heat flux of $Q = 2,000$ kW/m² results in a decrease in $M_{in}$ of 23%, 20.7%, and 47.3% for $\beta$ of 2, 1.50, and 1.01 respectively.

Effects of various surface roughness cases on $M_{in}$ are compared within each other and with the isentropic flow in Table 1. As in the heat flux discussions, surface roughness produces lower $M_{in}$ values, thus mass flow rates, for all $\beta$ and $Q$ cases. In the specific case with heat flux of 2,000 kW/m², the application of the nondimensional surface roughness of $\varepsilon/D = 0.0025$ resulted in lower $M_{in}$ by 47.3%, 19.8%, and 21.9% for the $\beta$ of 1.01, 1.50, and 2, respectively, where else the corresponding decrease rates for $\varepsilon/D = 0.025$ are 47.8%, 21.6%, and 23.8%. It is obvious that the reduction amounts for the lowest and highest roughness cases are close, indicating that $\varepsilon$ itself, whether small or big, is a resistive cause for gas motion even at high velocities of $0.1 < M < 1.0$. On the other hand, the decrease rates in Mach number, due to both heat flux and surface roughness runs, indicated higher amounts for the $\beta = 1.01$ flow, where the $M$ and mass flow rates are the smallest among the investigated sets. This implies that the roles of $\varepsilon$ and $Q$ are more impressive for flows with $M \leq 0.15$ in constant area ducts.

The flow density is a measure of compressibility and the streamwise variations are displayed in nondimensional form by dividing each nodal data by the exit plane value and presented in conjunction with Mach number in Figure 4a as well. Regardless of the level of $\beta$ and $Q$, the exit density value appears to be the smallest among the complete flow volume, which can be attributed to the contributing highest Mach number at the exit. Contrary to the Mach number discussions, surface heat flux causes inlet density values to increase both in choked and unchoked flows. However, the influence of $\beta$ on density constitutes a complex structure and alters the way of impact in moderate ($0.6 < M < 0.8$) and low ($M < 0.2$) Mach number cases. Although the decrease in $M$ for lower $\beta$ ($2.00 < \beta < 1.50$) are accompanied with lower density ratios also, further decreasing $\beta$ ($\beta < 1.50$) augmented the $\rho/\rho_{ex}$ ratios. This can be explained by the
It can be seen that lower 

$$\varepsilon = 0.025$$ which as a result causes significant augmentations in static temperature values especially towards the exit. Since density is inversely proportional to static temperature (Eq. 2b), higher the exit static temperature value lower the exit density; thus the ratio of the inlet to exit density values becomes more remarkable ($$\beta = 1.01$$, $$Q = 2,000$$ kW/m², $$\rho_{in}/\rho_{ex} \approx 2.10$$). Table 2 shows that the surface roughness does not vary the ratio of $$\rho_{in}/\rho_{ex}$$ even slightly, however, inlet stagnation pressure and surface heat flux values are the main sources of compressibility and density variations.

Streamwise heat transfer coefficient ($$h$$) variations are evaluated for different $$\beta$$ and $$Q$$ cases, with the constant value of $$\varepsilon/D = 0.0125$$ and given in Figure 4b. It can be seen that lower $$\beta$$ and higher $$Q$$ resulted in lower $$h$$ both in the choked and unchoked conditions, which can be attributed to the lower $$M$$, $$U$$, and $$\bar{m}$$ values for lower inlet stagnation pressure with higher heat flux values as discussed through Figure 4a. It can be seen from the figure that in the flows with $$\beta = 1.50$$ and 2.00, heat transfer coefficient increases towards downstream; however, the contrary occurs for $$\beta = 1.01$$. The augmentation in $$h$$ towards downstream is an accompanied outcome of flow acceleration, and the ratio of the exit to inlet Nusselt numbers $$\lambda = h_{ex}/h_{in}$$ increase both with $$\beta$$ and $$Q$$; such as in the $$\beta = 2.00$$ flow the $$\lambda$$ are 1.27, 1.32, and 1.35 and in the $$\beta = 1.50$$ case as 1.07, 1.08, and 1.09 for $$Q$$ of 400, 1,200, and 2,000 kW/m², respectively. These findings agree well with those of Bartz [6], who reported augmented $$\lambda$$ ratios with higher $$\beta$$, also with the records of Ahmad [5] and Back et al.’s [4] $$\lambda$$ of 2.17 and 1.15, respectively. Due to the application of different heat flux values, heat transfer coefficient values vary by ±5.97% (at the inlet) and ±2.83% (at the exit) for $$\beta = 2.00$$ case within the complete $$Q$$ set whereas the corresponding intervals expand to ±17.38% and ±32.51% for $$\beta = 1.01$$. The limits indicate that the effect of $$Q$$ on heat transfer coefficient becomes more significant in lower $$\beta$$ cases, thus in low Mach number flows. Effects of $$\varepsilon$$ on the average heat transfer coefficient ($$\bar{h}$$) values, for various heat flux cases, are investigated by the application of three different $$\varepsilon/D$$ values of 0.0025, 0.025, and 0.025 and displayed in Table 3. The resistive effect of $$\varepsilon$$ on flow decreased $$\bar{h}$$ for all $$\beta$$ and $$Q$$ cases; particularly for the choked flow ($$\beta = 2.00$$), where the impact is more significant especially for the with a variation of 1.5%.

Figure 4(b) further presents friction force ($$F_f$$) variations, evaluated at constant $$Q$$ values of 400, 1,200, and 2,000 kW/m², with constant $$\varepsilon/D$$ of 0.0125. Similar to the heat transfer coefficient discussions, higher $$Q$$ and lower $$\beta$$ caused $$F_f$$ values to decrease, especially, at the upstream sections; however, unlike $$h$$, $$F_f$$ curves converge towards the exit. Ribault and Friedrich [7] reported higher $$f$$ values with surface cooling which is in harmony with the present findings. From the definition of friction force (Eq. 3c), the above defined reducing effects of higher $$Q$$ and lower ($$\rho_{in}$$) on $$M$$ and $$\bar{m}$$ values explain the lower values of $$F_f$$ at the inlet section of the ducts. Table 4 presents the variation of total friction force ($$\Sigma F_f$$) with $$\varepsilon$$ for various $$Q$$ and $$\beta$$ cases. As expected, higher $$\varepsilon/D$$ resulted in higher $$\Sigma F_f$$ values in the complete $$Q$$ and $$\beta$$ set. On the other hand, independent of the level of $$\beta$$, the $$\Sigma F_f$$ values, evaluated for $$\varepsilon/D$$ of 0.0025 and 0.025, are separated by a factor of 2.06–2.08 for the complete $$Q$$

<table>
<thead>
<tr>
<th>$$\varepsilon/D$$</th>
<th>$$Q$$</th>
<th>$$\beta = 1.01$$</th>
<th>$$\beta = 1.50$$</th>
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Figure 5  (a) Influence of surface heat flux on the streamwise variations of stagnation temperature and pressure ratios, (b) variation of discharge coefficient with various $\beta$, $Q$, and $\epsilon$. 
Table 6 additionally demonstrates the combined ion temperature values are interrelated by Eq. 1b. static temperature, since the nodal static and stagnation outcome coincides with the above discussions on direction especially in low Mach number cases. The stagnation temperature values in the streamwise direction. However, the sources of nonisentropy, like surface roughness and heat flux, cause these properties to alter in the flow direction and, as explained in the Governing Equations section, prediction of their variations is of high importance in compressible flows. Figure 5a interprets the ratio of the nodal stagnation properties (subscript x) with those of the inlet, in the existence of various heat flux conditions. The stagnation pressure values decrease both in the flow direction and also with heat flux, where the streamwise decay is due to the constant surface roughness of $\varepsilon/D = 0.0125$ and can be clarified by the linear momentum equation (Eq. 4) expressing the dependence of static pressure variation, thus stagnation pressure through Equation 1(a), on the frictional term. The influence of heat flux is more apparent in higher $\beta$ cases with the most significant decrease rate of 4.7% in the flow with $\beta = 2.00$ and $Q = 2,000$ kW/m². On the other hand, as given in Table 5, the surface roughness does not produce any variation in the $P_{0,ex}/P_{0,in}$ ratio in low Mach number flows ($\beta = 1.01$) but results in lower ratios in moderate $\beta = 1.50$ and high $\beta = 2.00$ Mach number cases.

On the other hand, surface heat flux generates higher stagnation temperature values in the flow direction especially in low Mach number cases ($\beta = 1.01$) up to inlet to exit ratio of 2.08. This outcome coincides with the above discussions on static temperature, since the nodal static and stagnation temperature values are interrelated by Eq. 1b. Table 6 additionally demonstrates the combined effects of $\varepsilon$ and $Q$ conditions on the $T_{0,ex}/T_{0,in}$ ratio, where the surface roughness appears to be of minor importance on flow stagnation temperature data with 1% deviation in exit to inlet stagnation temperature ratio among the lowest and highest surface roughness cases.

Combined effects of $\varepsilon$, $\beta$, and $Q$ on the discharge coefficient ($C_d$) are given in Figure 5(b). Higher $\beta$ values resulted in higher $C_d$ for the complete $\varepsilon$ and $Q$ ranges, which indicates that $\beta$ is the dominant parameter on $C_d$, especially for the range of $1.01 < \beta < 1.50$. Our numerical results show, particularly for the $Q = 2,000$ kW/m² & $\varepsilon/D = 0.0025$ case, that $C_d$ data are 0.93, 0.90, and 0.53 for $\beta = 2.00$, 1.50, and 1.01, respectively. Also Park et al. [8], in their experimental work, and Ahmad [5], in his numerical investigation, determined augmented $C_d$ with higher $\beta$ in compressible flows. Application of $Q$ decreased the $C_d$, which contributes to Mach number variations with $Q$ (Fig. 4a), however, the $C_d$ gap among different heat flux cases decreases in higher $\beta$ cases, which show parallelism with the reports of Paik et al. [9]. Figure 5(b) moreover exhibits the influence of surface roughness on $C_d$, where the representative curves for different $\varepsilon/D$ cases almost coincide for $\beta = 1.01$ and branch out with higher $\beta$ and the difference become more distinguishable for $\beta > 1.50$. These determinations are in harmony with the $M_{0,in}$ data of Table 1, where surface roughness is determined to be more effective on Mach number in flows with high $\beta$.

**CONCLUSION**

A recent software tool for the numerical investigation of nonadiabatic and frictional duct flow is presented. The visual structure, database support, and the wide
variety of theoretical approaches, marching techniques, and surface/heat transfer definition models not only introduce GAS-DYN v2.0 as a reliable package for MSc and PhD level researchers but also show its applicability in the design phase of a complete compressible flow assembly. The computational analysis, carried out here, brings up the following outcomes for various inlet/boundary conditions from the point of flow and heat transfer characteristics:

- The Mach number and mass flow rate values decrease with lower $\beta$ and higher $\varepsilon$ and $Q$, where the roles of $\varepsilon$ and $Q$ are more impressive on Mach number in cases with lower $\beta$.
- Due to the augmented Mach numbers at the exit, exit density values appear to be the smallest among the complete flow volume; moreover, surface heat flux causes inlet density values to increase both in choked and unchoked flows.
- Lower $\beta$ and higher $Q$ resulted in lower convective heat transfer coefficients both in the choked and unchoked conditions, on the other hand the resistive effect of $\varepsilon$ on flow decreased convective heat transfer coefficient for all $\beta$ and $Q$ cases; where the impact is more significant in choked flows.
- The streamwise decay of stagnation pressure is due to $\varepsilon$, whereas $Q$ causes lower stagnation pressure values throughout the flow volume. On the other hand, $Q$ generates higher stagnation temperature values in the flow direction especially in low Mach number cases, however, $\varepsilon$ appears to be ineffective on flow stagnation temperature data.
- As discharge coefficient values are determined to increase with higher $\beta$ for the complete $\varepsilon$ and $Q$ ranges, application of $\varepsilon$ and $Q$ resulted the contrary on $C_d$ and surface roughness came out to be more effective in flows with high $\beta$.

REFERENCES