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Yurii Tereshchenko,
Illia Yudin

DETERMINATION OF QUANTITATIVE RELATIONSHIPS BETWEEN THE NON-DIMENSIONAL AXIAL LENGTH OF AN ANNULAR PRE-TURBINE MIXING CHAMBER AND THE INTEGRAL CHARACTERISTICS OF TEMPERATURE FIELD UNIFORMITY

The object of the research is the annular mixing chamber of the pre-turbine duct of a three-stream aircraft turbofan engine, designed to enforce the mixing of hot and cold flows within a confined axial geometry, with particular emphasis on the gas-dynamic and thermal processes occurring within it. The research problem addressed in this research was the determination of the minimally required relative length of the mixing chamber. This length must ensure an acceptable level of temperature uniformity at the turbine inlet without increasing the overall dimensions of the propulsion system. This condition is particularly critical for compact engines, including propulsion systems for unmanned aerial vehicles. A series of three-dimensional CFD simulations was performed using ANSYS Fluent with a Reynolds stress model (RSM) for turbulence. The modeling was conducted for an annular chamber with fixed geometric parameters (D = 1107 mm, d = 492 mm) within a range of relative lengths $L^* = 0.42–2.11$. The research covered four different engine operating conditions, varying in bypass ratio. The results revealed a clear nonlinear dependence of the temperature non-uniformity coefficient θ on the relative chamber length L^*. It was found that for $L^* < 1.2$, the mixing process remains incomplete, accompanied by a significant increase in temperature non-uniformity. In contrast, within the range $L^* = 1.2–1.7$, nearly complete temperature equalization is achieved ($\theta \le 0.1$). These results can be explained by the dominance of the turbulent mixing mechanism, as confirmed by low Richardson numbers ($R_i \ll 1$) and the minor influence of operating parameters compared to geometric factors. The findings can be applied in the design of compact mixing chambers for aircraft gas turbine engines, especially under strict constraints on their axial dimensions. This is particularly relevant for propulsion systems of unmanned aerial vehicles.

Keywords: *gas turbine engine, annular mixing chamber, temperature non-uniformity, turbulent mixing, CFD modeling.*

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1. Introduction

Recent trends in modern gas turbine engine (GTE) designs emphasize a new focus on identifying design architectures that will provide incremental performance improvements, as well as meet or exceed current stringent environmental and operational specifications [1]. Study [1] shows that the size and weight increase of large-diameter fans in classic architectures have caused an increase in research into multi-spool and three-stream architectures. However, unresolved issues remain related to the compact integration of additional streams. In particular, leading aviation nations are developing adaptive three-stream concepts (adaptive cycle engines) within the framework of the AETP programs (USA). These concepts envisage the introduction of an additional air stream with variable geometry to enable dynamic optimization of engine parameters across different segments of the flight profile [2, 3]. It has been shown that adaptive concepts improve cycle flexibility, but challenges persist in increased system complexity.

Alongside this, an alternative conceptual approach is being considered that involves the use of a permanently operating third stream integrated directly into the turbine module architecture [4]. In such a configuration, the third-stream airflow does not participate in the core thermodynamic cycle of the engine. It is directed to the peripheral regions of the turbine rotor blades, which are equipped with specialized profiled channels. Such blades operate based on the principle of a low-stage axial compressor and provide additional energy conversion of the flow. However, unresolved issues remain related to thermal durability and mixing efficiency. At the same time, a critical aspect of implementing this scheme is ensuring the thermal durability of the turbine blades, which materials – even when employing modern single-crystal superalloys with thermal barrier coatings – exhibit limited resistance to thermocyclic loading due to incomplete mixing. To reduce the number of temperature gradients acting on the blade from three to two, preliminary uniform mixing of the hot and cold stream flows prior to their entry into the turbine is required. As demonstrated in [5, 6], this process is implemented in an annular mixing chamber of the pre-turbine duct, where mixing quality significantly affects blade life.

The engineering challenge of designing a pre-turbine mixing chamber lies in the conflicting requirements imposed on its geometry. On the one hand, achieving effective turbulent mixing of flows with different temperatures requires a sufficiently long axial flow path. On the other hand, the overall length of the powerplant is a key parameter governing its mass, nacelle aerodynamic drag, and, consequently, the flight performance of the aircraft, while unresolved issues remain regarding the determination of the minimum required length.

This issue becomes particularly acute in the context of the rapid development of unmanned aerial vehicles, for which flight endurance, autonomy, and minimization of operating costs are of paramount importance. In the design of propulsion systems for operational-strategic class UAVs, especially those employing a pusher-propeller configuration, the dimensions of the engine nacelle are severely constrained. This substantially limits the allowable length of all gas-path components, including the mixing chamber, and precludes the use of conventional elongated mixing chambers. Under such conditions, the search for an optimal balance between the geometric parameters of the mixing chamber and the quality of mixing becomes a key engineering problem, upon which solution the durability and efficiency of the entire propulsion system depend [7], while questions remain regarding predictive parameterization.

Therefore, the relevance of the present research is driven by the need to develop a scientifically grounded method for parameterizing the length of the pre-turbine mixing chamber for advanced GTE architectures. This method enables the prediction of the minimum required flow-path length to achieve a prescribed level of temperature uniformity based on an analysis of the chamber's geometric parameters, as a possible way to overcome the identified difficulties.

The classical approach to solving such problems is based on performing a large number of parametric simulations or experiments for each specific configuration. Despite the possibility of obtaining accurate results in individual cases, this approach is resource-intensive, and the derived empirical correlations often exhibit limited predictive capability when the scale, bypass ratio, or operating conditions are varied. An alternative is to identify generalized physical regularities by describing the processes in terms of a system of dimensionless similarity criteria that reflect the fundamental mechanisms of turbulent transport and remain valid over a wide range of conditions [8, 9]. In this context, the problem of selecting the optimal chamber length L is transformed into the determination of an optimal dimensionless length $L^* = L/D_h$, where D_h is the hydraulic diameter of the mixing chamber, which can be considered a potential approach to overcoming these limitations.

The theoretical foundations of turbulent mixing of flows non-uniform in temperature and velocity are comprehensively presented in fundamental studies [8–10]. Similarity criteria are crucial when analyzing these types of processes. The Richardson number (R_i) is the most important of them due to its ability to assess the influence of buoyant forces on the stability of the shear layer and the strength of heat and mass transfer [11], although unresolved issues remain in confined high-pressure ducts.

There has been a significant amount of research in the area of gas turbine engineering on the processes of mixing in engine exhaust systems to reduce the noise and temperature of exhaust jets [12] as well as the optimization of processes in multi-stream combustion chambers [13]. The transferability of these results to pre-turbine conditions remains uncertain, since exhaust systems operate under markedly different flow conditions.

The reason is that the pre-turbine duct has significantly different conditions than those found in the engine exhaust systems – elevated pressure levels, high gradients of inlet parameters, and limited axial length particularly in compact propulsion systems [14], which may explain the lack of generalized design methodologies, a gap that this study addresses using similarity-based criteria.

Unlike prior studies limited to specific geometries [8, 9] or exhaust conditions [12, 13], this work establishes similarity-based relationships between chamber length and temperature uniformity, enabling predictive design under compact axial constraints.

A review of current scientific literature shows there have been no systematic investigations into the quantitative relationship between the dimensionless geometric parameters of a pre-turbine annular mixing chamber and the overall performance parameters of the temperature field. In particular, there have been no investigations into the effect of the relative chamber length (L^*) on the temperature non-uniformity coefficient (θ) under different engine operating conditions, nor how these effects may be related to the parameters describing the flow distribution between the two streams. Therefore, it is essential to fill the scientific gap described above, in order to create generalized design methodologies for compact pre-turbine mixing chambers. The scientific novelty of this research lies in establishing, for the first time, quantitative similarity-based relationships between the dimensionless geometric parameters of the pre-turbine annular mixing chamber and the integral characteristics of the temperature field.

This research focuses on the turbulent mixing process of gas flows with different temperatures in an annular mixing chamber of the pre-turbine duct of a gas turbine engine, taken as a generalized representation of compact turbofan and prospective multi-stream engine architectures.

The object of research is the annular mixing chamber of the pre-turbine duct of a three-stream aircraft turbofan engine, designed to enforce the mixing of hot and cold flows within a confined axial geometry, with particular emphasis on the gas-dynamic and thermal processes occurring within it.

The aim of this research is to define quantitative relations between the dimensionless axial length of an annular pre-turbine mixing chamber and the overall characteristics of the temperature-field uniformity at the turbine inlet, by applying similarity criteria, thereby providing the scientific basis for establishing the minimum required chamber length, given the strict geometric constraints.

To implement the aim, the following specific research objectives were developed:

1) to carry out a three-dimensional numerical simulation of turbulent mixing in an annular pre-turbine chamber for a range of dimensionless axial lengths;

2) to investigate the role of similarity criteria, specifically the Richardson number, in creating the temperature field;

3) to define the dependence of the temperature non-uniformity coefficient on the relative chamber length for characteristic engine operating conditions.

The research assumes a generalized annular mixing chamber, representative of both conventional turbofan and prospective three-stream engine configurations.

2. Materials and Methods

The subject of research is the influence of the dimensionless axial length of the annular mixing chamber on the integral characteristics of the outlet temperature field at the turbine inlet.

Research Methods: The research was conducted by means of three-dimensional numerical simulation. Calculations were conducted by

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means of the ANSYS Fluent software package in a steady state mode. The numerical solutions to the Navier-Stokes equations for a compressible gas are included along with the energy equation. The primary stream was modeled as combustion products, and the secondary stream as bypass air, both treated as compressible ideal gases with temperature-dependent thermophysical properties. The dynamic viscosity was calculated using Sutherland's law. Chemical reactions were not considered, since the mixing process was studied downstream of the combustion zone. The utilized software package was ANSYS Fluent (ANSYS Inc., USA), for all of the numerical simulations. For each of the governing equations, second order discretization methods were utilized so that sufficient numerical accuracy could be achieved. The numerical method applied corresponds to the general recommendations for Reynolds averaged simulation of turbulent internal flows in accordance with standard CFD guidelines and literature concerning gas turbine internal aerodynamics [15].

A grid independence study was performed to minimize the influence of spatial discretization on the numerical results. Several meshes with increasing cell counts were tested, and the final mesh was selected based on the stabilization of the integral temperature-field parameters. The selected mesh was a hybrid polyhedral mesh with prism layers near the walls, consisting of approximately 4 million cells, providing sufficient resolution of the flow and temperature fields. The near-wall mesh was designed to maintain y^+ values below unity, ensuring proper resolution of the viscous sublayer. Solution convergence was assessed using residual reduction criteria and by monitoring integral flow parameters. The calculations were considered converged when the normalized residuals for all governing equations dropped below 10^{-5} and the monitored temperature non-uniformity coefficient reached a steady value.

For the description of turbulent phenomena, the Reynolds Stress Model (RSM) was selected since it allows accounting for the anisotropy of turbulence and to precisely represent the structure of shear layers in flows characterized by strong velocity and temperature gradients. The application of this method is suitable for the investigation of the mixing process in the case of strongly stratified flows where there is a significant interaction between the turbulent transport and buoyancy forces. Previous test calculations using two-equation models (k–ε and k–ω, SST) did not show satisfactory results in the reproduction of the temperature gradient in the inlet shear layer, thus the RSM was finally selected.

Validation of the applied approach: Previous studies have shown the correctness of the combination of the ANSYS Fluent environment with the RSM turbulence model for the investigation of the turbulent mixing in annular ducts by comparing the calculation results with the experimental data [16]. The boundary conditions at the inlets were assigned in terms of the total pressure and total temperature, which corresponded to the typical operating regimes of the engine. At the outlet of the mixing chamber, the boundary condition was assigned as an outflow, i. e. a completely developed flow with zero diffusion fluxes for all flow parameters. The level of turbulence intensity at the inlet of the hot flow was set equal to 5%; while at the inlet of the cold flow it was set equal to 3%. The methodology has been applied to the analysis of thermal and aerodynamic processes in the pre-turbine ducts of gas turbine engines. The described numerical methodology ensures reproducibility of the obtained results and can be applied to annular mixing chambers.

3. Results and Discussion

3.1. Three-dimensional numerical simulation of turbulent mixing in an annular chamber

The results presented in this section are structured in accordance with the formulated research tasks and are aimed at revealing the influence of the dimensionless axial length of the annular mixing chamber on the integral characteristics of temperature-field uniformity.

An annular mixing chamber was considered, which geometry corresponds to a typical configuration of the pre-turbine duct of a modern turbofan engine (Fig. 1). The fixed geometric parameters defining the baseline configuration are:

– outer channel diameter, D = 1107 mm;
– phase interface diameter, d^* = 800 mm;
– inner diameter (hub diameter), d = 492 mm.

Based on these parameters, the equivalent hydraulic diameter of the cross-section was calculated as $D_h = D - d$ = 615 mm, which is subsequently used to define the dimensionless length.

The axial (effective) length of the chamber L was the primary geometric parameter varied in this research. For the parametric analysis, five chamber lengths were selected, covering a range from strongly shortened to relatively developed ducts: L_1 = 260 mm, L_2 = 520 mm, L_3 = 780 mm, L_4 = 1040 mm, and L_5 = 1300 mm. The corresponding values of the relative length are: $L_1^* = L_1/D_h \approx 0.42$, $L_2^* \approx 0.85$, $L_3^* \approx 1.27$, $L_4^* \approx 1.69$, and $L_5^* \approx 2.11$.

This approach makes it possible to investigate the evolution of the mixing process along the chamber and to assess the effect of duct length limitation on the final quality of the temperature field.

Inlet conditions:

Primary (core) stream: T_k^* = 756 K, 850 K, 935 K, 1015 K. Secondary (bypass) stream: T_f^* = 306.5 K, 333 K, 354.7 K, 373.7 K. Total Pressure at the inlet: p_T^* = 151987.5 Pa, 202650 Pa, 253312.5 Pa, 303975 Pa.

The optimal bypass ratio was determined from the following expression

$$m_{opt} = \frac{\overline{m} \cdot \Delta \cdot \eta_T \cdot \eta_{II} \cdot \left(1 - \frac{e_{fII}}{e_k}\right) - \left(e_k - 1\right) \cdot \frac{\eta_{II}}{\eta_K}}{\left(e_{fII} - 1\right)}, \quad (1)$$

where $\overline{m}$ – flight-condition correction coefficient; Δ – total temperature ratio in the cycle; η_T – turbine efficiency; η_{II} – fan efficiency; e_{fII} – fan pressure ratio; e_k – core compressor pressure ratio; η_K – compressor efficiency.

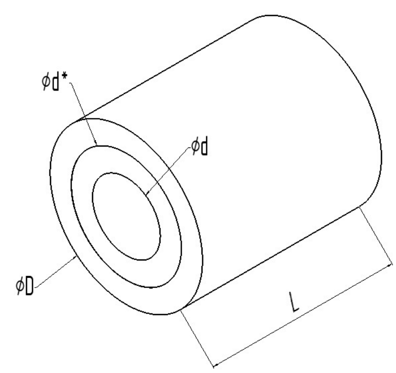

Fig. 1. Schematic of the mixing chamber

After the numerical solution of the problem and analysis of the results, the obtained dependencies of the mixed-flow temperature on the optimal bypass ratio were summarized in Fig. 3–5.

3.2. The role of similarity criteria in temperature field formation

To generalize the results and transition from specific geometric dimensions to universal relationships, the mixing process was analyzed using two fundamental dimensionless parameters – the relative chamber length L^* and the Richardson number R_i.

1. *Relative length L^*:* This parameter serves as the primary geometric criterion of the mixing process, as it relates the axial scale of flow development to the characteristic transverse dimension of the chamber. Physically, L^* characterizes the available space for the evolution of turbulent vortical structures that govern the intensity of mass and heat transfer. Small values of L^* correspond to conditions in which the shear layers formed at the inlet do not have sufficient distance to fully

develop and interact with each other, leading to the persistence of significant temperature non-uniformities. As L^* increases, the duration of flow interaction grows and conditions are created for multistage breakdown of vortical structures, which promotes more intensive thermal equalization.

2. *Richardson number:* The Richardson number was determined using the following relationship

$$R_i = \frac{g \cdot d_h \cdot \left(\frac{\Delta T}{T_{avg}}\right)}{u^2}, \qquad (2)$$

where g – the acceleration due to gravity; ΔT – the characteristic temperature difference between the hot and cold streams; u is the characteristic flow velocity; d_h – characteristic mixing length scale; T_{avg} – the average temperature is defined as the mass-averaged temperature of the total flow at the mixing chamber inlet.

Within the scope of this research was taken to be equal to the mean velocity of the hot stream at the chamber inlet.

The Richardson number is a criterion expressing the ratio between buoyancy forces, generated by thermal non-uniformity and density stratification, and inertial forces that govern the level of forced convection and turbulent mixing. Under the following conditions:

– $R_i \ll 1$, forced convection dominates, and heat transport is carried out predominantly by turbulent velocity fluctuations;

– $R_i \gg 1$, free-convection effects prevail, accompanied by a tendency toward flow stabilization and the formation of stratified regions.

In annular mixing chambers of turbofan engines operating under conditions of intense velocity gradients, the regime $R_i \ll 1$ is physically typical. Nevertheless, a quantitative analysis of the influence of this parameter remains necessary for a correct assessment of the possible extent of gravitational effects on mixing quality.

3.3. Effect of relative length on temperature non-uniformity factor

The efficiency of thermodynamic equalization was evaluated using the temperature non-uniformity coefficient θ, which was determined at the outlet cross-section of the mixing chamber

$$\theta = \frac{T'_{\max} - T'_{\min}}{T'_{avg}}, \qquad (3)$$

where $T'_{\max}$, $T'_{\min}$, and T'_{avg} – the maximum, minimum, and mean flow temperatures at the outlet of the mixing chamber, respectively. This is the most fundamental qualitative measure of the spatial temperature distribution and is a commonly used criterion in the design of gas turbine engines for the allowable thermal loadings of turbine blades. Low values of θ indicate a greater uniformity of the temperature distribution and thus better conditions for operation of the turbine. Therefore, minimizing θ is the main goal of the optimization process.

Based on the analysis of the results of the numerical computations, the relationship between the basic performance criterion, namely the temperature non-uniformity coefficient θ, and the dimensionless length of the mixing chamber L^*, depending on the bypass ratio m, was constructed (Fig. 2).

The overall behavior of all curves indicates an increase in θ when the length of the mixing chamber decreases. However, the curves corresponding to the different values of m are located within a relatively narrow correlation band (the variation in θ is less than 0.02 at fixed L^*), and therefore the geometric parameter L^* dominates over the operational parameter m in the examined range.

Two distinct zones can be identified on the $\theta(L^*)$ dependence:

– active interaction zone ($L^* < 1.2$).

When the dimensionless length L^* is increased from the lower limit, the sharp decrease in θ (about 40–60%) indicates the transition from an incomplete mixing regime to a fully developed turbulent exchange.

– zone of asymptotic saturation ($L^* > 1.7$).

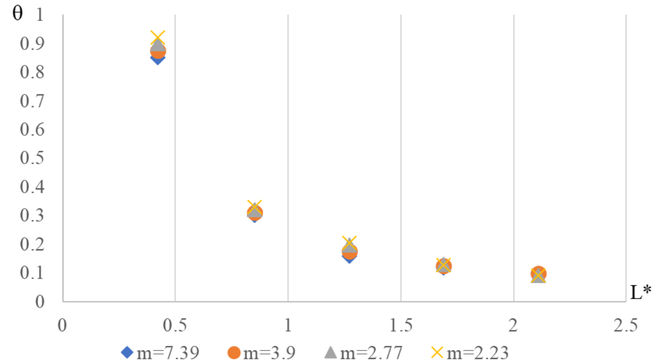

Fig. 2. Relationship between the temperature non-uniformity coefficient ϑ and the dimensionless length of the mixing chamber L^*, for various values of the bypass ratio m

Increasing the length of the mixing chamber further beyond the value of $L^* = 1.7$ results in only minor improvement in the mixing quality ($\Delta\theta < 0.03$), and therefore the mixing process is effectively complete.

Fig. 3 presents the static temperature fields at the outlet of the mixing chamber for three length configurations: $L = 1300$, 780, and 260 mm. As shown in Fig. 3, a reduction in the mixing chamber length leads to a noticeable deterioration in the uniformity of the outlet temperature field.

In the chamber with a length of $L = 1300$ mm (Fig. 3, *a*), the flow demonstrates a satisfactory degree of mixing: the temperature distribution is relatively uniform, pronounced hot and cold regions are absent, and the non-uniformity coefficient θ reaches its minimum values.

In contrast, in the shortest chamber ($L = 260$ mm, Fig. 3, *c*), the mixing process does not have sufficient time to fully develop due to the limited residence time of the interacting streams. As a result, significant temperature pulsations and local overheating zones are observed at the outlet section, indicating high values of θ and incomplete flow equalization.

For the chamber of intermediate length ($L = 780$ mm, Fig. 3, *b*), a transitional regime is observed: the outlet temperature field is nearly uniform; however, the region of intensive turbulent mixing has already formed, ensuring a noticeable reduction in temperature gradients compared to the short chamber configuration.

This behavior agrees with the common concepts regarding the development of turbulent mixing in confined channels. The asymptotic saturation limit of the mixing process is attained in the pre-turbine mixing chamber at lower values of the relative length compared to those reported in well-known studies of exhaust and post-turbine ducts. This is due to higher pressure levels and stronger shear layers in the pre-turbine mixing chamber.

From the point of view of compactness and efficiency, the optimal interval of the relative length of the mixing chamber is $L^* = 1.2–1.7$. At these values of the relative length, values of $\theta \leq 0.1$ are attainable, which corresponds to a good uniformity of the temperature distribution.

In all studied cases, the Richardson number was in the range $R_i = 0.01–0.06$, and therefore the inertial forces dominated the buoyant forces and the turbulent mixing mechanisms were prevailing over the effect of buoyancy. Nevertheless, even within this range, a clear trend was found: increasing R_i resulted in a slight but systematic increase in θ (in average by 4–6%). This behavior corresponds to the physical model according to which increased stratification suppresses the transverse turbulent transport.

To check whether the numerical model adequately describes the problem, the dependence of the mean outlet temperature T'_{avg} on the relative length L^* of the mixing chamber and the bypass ratio m was analyzed (Fig. 4). The results demonstrate that T'_{avg} depends only on the inlet thermodynamic parameters (via m_{opt}) and is practically independent of L^* (deviations do not exceed 0.5 %). Therefore, the results confirm that the energy conservation law was correctly implemented in the model, and variations in L^* affect only the spatial structure of the temperature distribution (non-uniformity θ) and not its integral energy content.

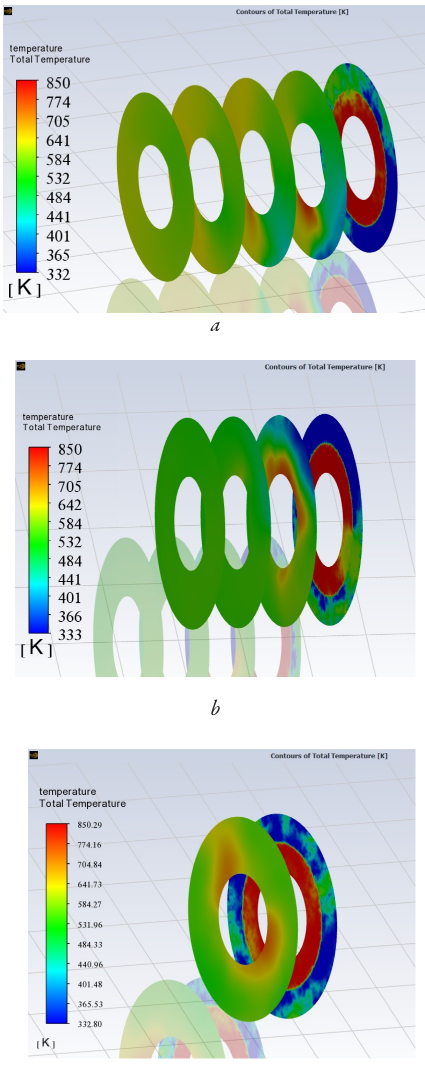

Fig. 3. Temperature fields at the outlet of the mixing chamber for three length configurations L = 1300, 780, and 260 mm at m = 3.9 (temperature field averaging in accordance with the adopted CFD procedure)

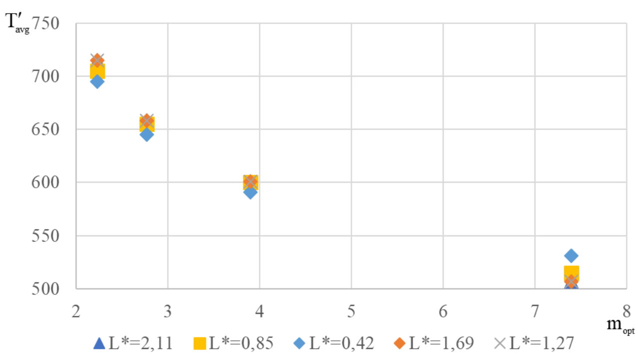

Fig. 4. Relationship between the mean outlet temperature on the bypass ratio m and the relative chamber length L^*

To interpret physically the obtained $\theta(L^*)$ dependence, the longitudinal distributions of the maximum, minimum and mean temperatures along the mixing chamber were analyzed for the case of the best compromise bypass ratio m_{opt} = 3.9 (Fig. 5). The resulting profiles show that the primary equalization of the temperature distribution takes place in the zone $L^* \approx$ 1–1.5, and then an asymptotic convergence of temperatures follows, which is in agreement with the behavior of the integral indicator θ.

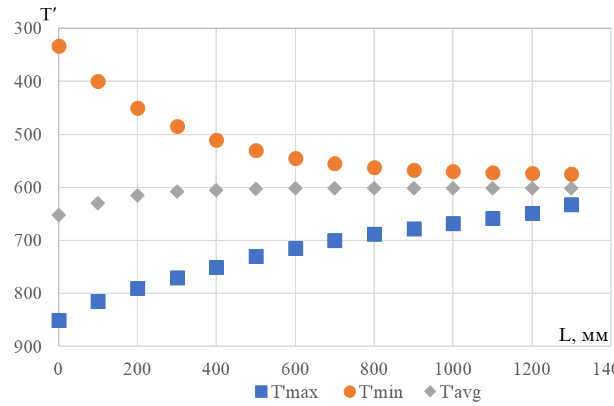

Fig. 5. Longitudinal variation of the maximum, minimum and average temperature along the mixing chamber for m_{opt} = 3.9

3.4. Discussion

The analysis of the results of the numerical simulation has provided a quantitative description of the temperature mixing process in the annular chamber and has formulated the influence of its main geometric parameter on the temperature non-uniformity coefficient. It was demonstrated that the dependence of the temperature non-uniformity coefficient on the relative length, $\theta(L^*)$, shows a universal character for the examined conditions of operation. A distinctive feature of the obtained results is the identification of a universal dependence $\theta(L^*)$, which makes it possible to determine the rational axial length based on dimensionless parameters independent of specific scale. This ensures practical applicability of the proposed approach at the preliminary design stage of compact propulsion systems. From the viewpoint of the design engineer, the important range is $L^* \approx$ 1.2–1.7, where the transition from the incomplete mixing with large temperature gradients to the state of almost complete mixing occurs. The results of the present research constitute a factual basis for formulating practical recommendations concerning the choice of the mixing chamber length, considering the interrelation between the process efficiency and the geometrical limitations, which is particularly important for propulsion systems of unmanned aerial vehicles.

Scientifically, this investigation represents an innovative development as a result of establishing a quantitative relationship between the ratio of the axial length and the total thermal-mixing characteristics of the annular pre-turbine mixing chamber, under conditions that correspond to the multi-stream structural configurations of engine components.

The results presented above have been obtained on the basis of a steady-state numerical formulation of the problem and the application of the RSM turbulence model, in which the time-dependent nature of the flow and its fluctuations are averaged out. Unsteady effects, pressure oscillations, and full conjugate interaction with the real rotating turbine blade row have not been considered, which limits the applicability of the results to steady averaged flow conditions. Moreover, the present research has been carried out within a limited range of thermodynamic parameters and geometric ratios typical of compact pre-turbine ducts, which define the boundaries of applicability of the derived relationships. Therefore, the derived relationships should be applied within the investigated ranges of Reynolds number, Richardson number, and geometric ratios. The obtained regularities can be explained by the dominant role of turbulent diffusion and buoyancy interaction in confined annular channels, which govern the rate of temperature equalization along the axial direction.

Further research should focus on the examination of unsteady effects of the mixing process, consideration of the impact of the rotating turbine blade rows and expansion of the ranges of geometric and operating parameters. Of special interest is the investigation of the mixing processes in the three-stream configurations and experimental verification of the obtained dependences. An additional promising direction is the refinement of the proposed model through high-fidelity simulations and experimental validation under extended operating conditions.

4. Conclusions

1. It was found that the relative axial length of the mixing chamber L^* is the most significant geometric characteristic which determines the distribution of the outlet temperature. The dependence of the temperature non-uniformity coefficient θ on L^* shows a clear non-linear behavior divided into two zones: zone of intense development of the mixing process ($L^* < 1.2$), and zone of saturated mixing ($L^* > 1.7$). The description of these behaviors shows how the geometrical limitation of the axial size of the mixing chamber influences the quality of the mixing process. It has been shown that the effect of operational parameters within the analyzed range is lower than the effects of geometrical ones. For all the investigated bypass ratios m_{opt}, the variations of $\theta(L^*)$ are contained in a narrow range; similarly, the Richardson number R_i are included in the interval $R_i = 0.01–0.06$. Analysis of the Richardson number showed that the effect of inertial turbulent mixing on the stratification generated by buoyant forces may be neglected. This result confirms the universal nature of the described regularities for the considered fluid dynamic regime.

2. The optimal range of the relative length of the mixing chamber, defined using a criterion, has been found. The optimal range is $L^*_{opt} = 1.2–1.7$. This range is characterized by the best compromise between the mixing quality and compactness, ensuring an excellent quality of temperature uniformity ($\theta \leq 0.10$) with the lowest possible axial length of the mixing chamber. Further increase of L^* beyond 1.7 yields negligible improvement ($\Delta\theta < 0.03$), which does not justify additional axial extension. Quantitatively, the obtained optimal range allows reducing the axial length of the mixing chamber, compared to traditional design methods, up to 30–40%, maintaining acceptable levels of temperature uniformity.

3. The established dependence of the temperature non-uniformity coefficient on the relative chamber length provides a foundation for a novel engineering design methodology for propulsion systems. The stability of the energy balance was confirmed, as deviations in the mean outlet temperature did not exceed 0.5%, indicating that variations in L^* affect only the spatial temperature distribution and not the integral energy content of the flow. It has been quantitatively demonstrated that operating within the optimal range of relative length ($L^* = 1.2–1.7$) ensures a temperature non-uniformity coefficient $\theta \leq 0.1$, corresponding to a 40–60% reduction in temperature non-uniformity compared to undersized configurations ($L^* < 1.2$). The application of the proposed generalized relationships at the initial design stage may enable a reduction in the axial length of the mixing chamber by 30–40% while maintaining acceptable temperature uniformity, which in turn, can significantly reduce the number of costly parametric CFD analyses required for final design optimization.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating the submitted work.

Authors' contributions

Yurii Tereshchenko: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – review and editing; ***Illia Yudin:*** Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing – original draft, Writing – review and editing.

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Yurii Tereshchenko, *Doctor of Technical Sciences, Professor, Department of Aviation Engines, National University "Kyiv Aviation Institute", Kyiv, Ukraine, ORCID: https://orcid.org/0000-0003-4367-3232*

✉ ***Illia Yudin,*** *Corresponding author, PhD Student, Department of Aviation Engines, National University "Kyiv Aviation Institute", Kyiv, Ukraine, ORCID: https://orcid.org/0009-0001-9934-553X, e-mail: illiayudin98@gmail.com*

✉ *Corresponding author*