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Axial Compressor surge protector and its Effects on Gas Turbine Detonation

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Abstract: The new idea in this paper is the effect of the occurrence of the surge phenomenon at the low flow rates on the lack of combustion inside the combustion chamber and the extent of its effect on stopping explosions in the gas turbine and causing the device to stop working completely. So, it was necessary to determine the beginnings of the occurrence of the phenomenon of flow instability (surge) inside the compressor, and thus its impact on the occurrence of combustion cessation in the gas turbine combustion chamber. The onset of flow instability due to rotary stall formation was revealed using the rolling mathematical model of energy transfer by separating the flow of the rotating blades from the diffuser cascades. This was verified using a closed-piston automatic compensation system synchronized with air inoculation over the reed controller. A feedback control system has been implemented to eliminate surge and rotating stalls. The mathematical solution model of Moore-Greitzer was developed to include the effect of air pollination on the compressor inlet on system performance and stable operating range. This method of controlling the surge inside the compressor from the full wall vibration along with the injection through the reed valve gave an increase of 29% in the range of stable operation of the compressor and thus improved the combustion process and the non-interruption of the flame inside the gas turbine combustion chamber. Numerical simulations of the detonation processes inside the gas turbine combustion chamber were performed to sense the beginnings of incomplete combustion using the ANSYS CFX program. The results show the extent of the development of flame spread and continuous and intermittent explosions at different flow rates, and the results showed acceptable agreement with the mathematical model.

Keywords: Axial flow compressors; Flow separation; Surge control; Blowoff; Gas Turbine

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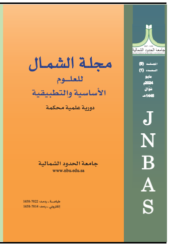

واقي التيار للضاغط المحوري وتأثيره على تفجير توربينات الغاز

أحمد سيد أحمد حسن

(قدم للنشر في 1444/11/12هـ؛ وقبل للنشر في 1445/4/16هـ)

مستخلص البحث: يدرس هذا البحث طريقة التحكم في مشاكل انقطاع تدفق الهواء عبر الضاغط المحوري نتيجة تكون دوامات الهواء والسريان العكسي، وكيفية قمع تذبذب الضغط وتأثيره على اتمام عملية الاحتراق فى التوربينات الغازية باستخدام نماذج رياضية مختلفة. تم الكشف عن بداية عدم استقرار التدفق بسبب تكوين المماطلة الدوارة باستخدام النموذج الرياضي لنقل الطاقة عن طريق فصل تدفق الشفرات الدوارة عن شلالات الناشر. تم التحقق من ذلك باستخدام نظام تعويض تلقائي بمكبس مغلق متزامن مع تلقيح الهواء فوق وحدة تحكم القصب. تم تطبيق نظام التحكم في التغذية الراجعة للقضاء على زيادة الضغط والأكشاك الدوارة. تم تطوير نموذج الحل الرياضي الخاص بـ Moore-Greitzer ليشمل تأثير تلقيح الهواء على مدخل الضاغط على أداء النظام ونطاق التشغيل المستقر. هذه الطريقة للتحكم في التدفق داخل الضاغط من اهتزاز الجدار الكامل مع الحقن من خلال صمام القصب أعطت زيادة بنسبة 29٪ في نطاق التشغيل المستقر للضاغط وبالتالي تحسين عملية الاحتراق وعدم انقطاع الاحتراق واللهب داخل غرفة احتراق التوربينات الغازية.

كلمات مفتاحية: ضواغط التدفق المحوري، فصل التدفق، المماطلة، التحكم في الطفرة، نفخ، توربينات الغاز.

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Nomenclature:		r_2	Rotor exit radius, mm
B	Nondimensional parameter, $B=U/(2\omega_H L_c)$	U	Rotor tip speed, m/s
h	Throttle coefficient	Φ	Non dimensional flow rate = $Q/2\pi b_2 r_2 U$,
L_c	Axial compressor length	Ψ	Non dimensional pressure rise $=2\Delta P/\rho U^2$
L_T	Throttle length, mm	μ	Nondimensional speed, $\sigma/(\omega_H L_c)$
m	Mass flow, kg	λ	Nondimensional duct length $=x_c/x_T$,
P	Pressure, Pa	x_c	Nondimensional comp. length $=L_c/A_c$,
ΔP_c	Pressure diff. bet. comp. inlet and exit, Pa	x_T	Nondimensional thr. length, L_T/A_T
ΔP_p	Pressure bet. plenum. inlet and exit, Pa		

1. Introduction

Nowadays, most commercial and military aircraft are powered by gas turbine engines with axial flow compressors for compressing the air inside the combustion chamber. These compressors are characterized by smaller diameter, lighter weight, and greater capacity to produce high-pressure ratios. On landing, the aircraft does not require a large power from the gas turbine, and then the compressor draws in a small amount of air that leads to the compressor working at the surge point. These phenomena usually occur at high altitudes with impact, leading aircraft engines to catastrophes. Eddy inflows may be utilized in gas turbine combustion to achieve strong flame stability over a wide range of operating conditions (Hongliang, Juan,, Wenqiang, Hongwu, & Chaoqun (2023), and Syred, & Beér (1974). The critical condition that occurs to the aircraft engine or so called surge that leads to engine breakdown was studied (Ciardiello, Gordon & Epaminondas (2020). Points of detonation and re-ignition, as well as the temperature and mass flow rate required for both blowing and re-ignition, and finding the energy for re-ignition and detonation, are detected (Mohamed, Jonggeun & aJeekeun (2023).

Designing a gas turbine combustion device is one of the most complex systems due to high-efficiency requirements and lower emissions with alternative fuels. Researchers (Sharma, and Tarnacha (2021), Dan, and Ahmed (2016), Nicholas, Ben, Jerry & Tim (2020) use high levels of computational mathematics of computational fluid dynamics and software to increase the speed and accuracy of the design. Burning permanency means smooth combustion and the ability of the flame to remain alight over a wide operating range (Wu, Zhao, Roy, Cetegen, Xu, & Lu, (2019). Operation of a gas turbine requires widespread, stable fuel combustion without combustion stalling or intermittent impulse flow, and the combustion efficiency must be close to 100% (Roy & Cetegen (2018). Detonation occurs in gas turbine combustion due to severe combustion instability and leads to flame extinction. It becomes very dangerous when the flow conditions from the compressor to the combustion chamber are unstable due to rotating stalls or surge (Roy & Cetegen 2020). A set of hypotheses and physical models have been developed to explain the detonation phenomenon and to define the flame properties as a function of gas mixture approach velocity and flow oscillations (Emerson, Jagtap, Quinlan, Renfro, Cetegen & Lieuwen, (2016), and Swetaprovo, Stanislav, Michael & Baki (2012). Although the temperature of the inlet flow is low and not enough for re-ignition, the temperature of the chamber walls is sufficient for re-ignition and initiation of detonation (Anna-Maria; Giusti & Allison, (2018), Giusti, and Mastorakos (2017), Kypraiou, Giusti, Allison, & Mastorakos, (2018), Roberto, Rohit, Ingrid & Epaminonds (2022), Navin & Satyanarayanan (2023), Marcum, Rachow, Ferkul & Olson (2020), James, Massey, Chena, Michael, Wolfgang & Nedunchezhian (2022), Ahmad, Shijie, Kar, Xue, & Mehdi, (2022), Pathania, El Helou, Skiba, Ciardiello & Mastorakos (2022).

However, the problem of intermittent ignition remains due to the presence of the surge that is the result of the appearance of intermittent flow. Therefore, this article focused on how to extinguish the surge phenomenon or cut off the flow coming into the combustion chamber. Surge occurs (Pathania, Skiba, Ciardiello & Mastorakos, (2021)) at low flow conditions, and control must be made to avoid it and remove it outside the compressor due to its seriousness. A surge in current is an instability that affects the entire compression system and downstream of the compressor and makes mass flow negative for parts of the burst cycle and detonation stops (Muhammad, Khalid & Arslan (2021). It is concluded from the summary of the articles presented in this article that the detonation phenomenon occurs at the same rate as the surge flow condition. A control action is required to avoid and remove the surge out of the compressor, as it is a cyclic phenomenon and repeats itself.

2. Compression system modeling without controller

Figure 1 shows an axial compression system modeling similar to Moore and Gretzer (Moore & Greitzer (1986)), as a Helmholtz resonator with actuated disk in the tube symbolizing the compressor and to the manifold that releases fluid through the throttle. The system is described by conserving momentum and mass throughout the system using a harmonic mechanical oscillator such as the air mass flowing in the tube is equal to the oscillating mass, the amplitude of the compression spring and the throttle as a damper with a completed wall constant is as follows:

$$l_c \frac{d\dot{m}}{dt} = \Delta P_c - \Delta P_p \tag{1-a}$$

$$\frac{\rho V_p}{\gamma P}\frac{dP_p}{dt} = \dot{m}_c - \dot{m}_T \tag{1-b}$$

$$l_T \frac{d\dot{m}}{dt} = \Delta P_p - \Delta P_T \tag{1-c}$$

$$\tau \frac{d\Delta P_c}{dt} = \Delta P_{css} - \Delta P_c \tag{1-d}$$

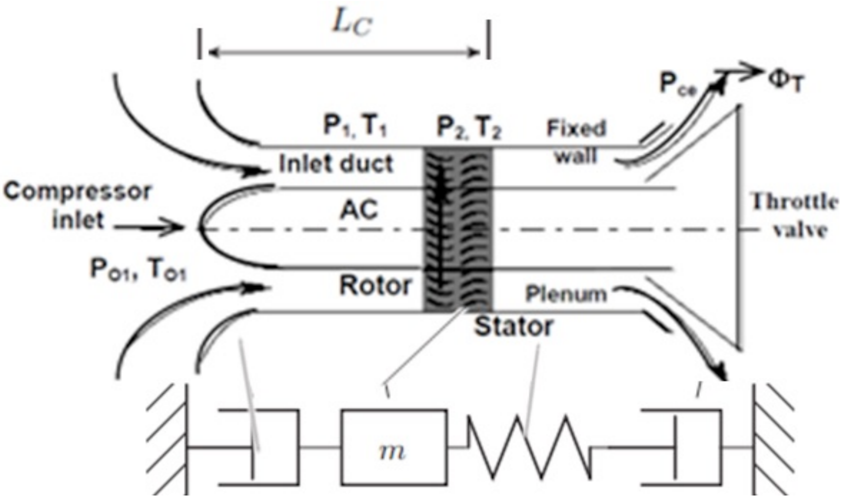


Figure 1: compression system model

Equ. (1) can be written in a nondimensional form as:

$$\frac{d\Phi_c}{d\tau} = B[\Psi_c(\Phi_c) - \Psi_p] \tag{2-a}$$

$$\frac{d\Psi_p}{d\tau} = \frac{1}{B^2}[\Phi_c - \Phi_T(\Psi_p)] \tag{2-b}$$

$$\frac{d\Phi_T}{d\tau} = \lambda B[\Psi_p - \Psi_T(\Phi_T)] \tag{2-c}$$

$$\frac{d\Psi_c(\Phi_c)}{d\tau} = \frac{1}{\tau}[\Psi_o(\Phi_c) - \Psi_c(\Phi_c)] \tag{2-d}$$

The axial compressor performance model as a polynomial function, $\Psi c(\Phi c)$ similar to (Mansoux, Gysling, & Paduano, (1994)) as:

$$\begin{aligned}
\Psi_c(\Phi_c) &= 12.117\Phi_c^2 - 2.423\Phi_c + 0.221; \quad \Phi_c \le 0.1 \\
&- 49.62\Phi_c^3 + 39.509\Phi_c^2 - 6.413\Phi_c + 0.395; \quad 0.1 < \Phi_c \le 0.4 \\
&- 10.0695\Phi_c^2 + 9.43\Phi_c - 1.184; \quad \Phi_c > 0.4
\end{aligned} \tag{3}$$

The crossing point between $\Psi_C(\Phi)$ and $\Psi_T(\Phi)$ has been the topic of numerous studies (Prasad, Neumeier & Krichene, (2000), Fontaine, and Kokotovic 2004) due to its importance in the safe, high-performance operation of axial flow compressor operations. The stable and unstable operation conditions, which represent all stationary solutions with different throttle closing conditions for Equ. 2 with Equ.3, are shown in Fig. 2. The solid line represents operating the compressor in steady operation or so-called design flow. When the throttle valve is slowly closed, the intersection point between $\Psi_C(\Phi)$ and $\Psi_T(\Phi)$ turns to decrease the flow rate and mild surge cycle appears. When more closed to a low flow rate, a deep surge occurs. It is clear from the figure that operating the compressor in the presence of unsteady flow decreases the amounts of air required for combustion and reduces the efficiency of the whole gas turbine since suppressing any condition of surge must be denoted.

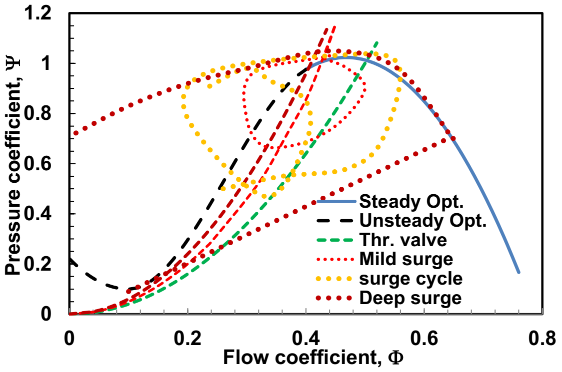


Figure 2: Compressor performance during steady operation and surge

3. Surge protector

To suppress the surge and ensure continuous combustion in the gas turbine, the air was injected through the reed valve as shown in Fig.3, and a vibratory wall was made to compensate for the flow. The effect of the controller on the stability of the system has been described as:

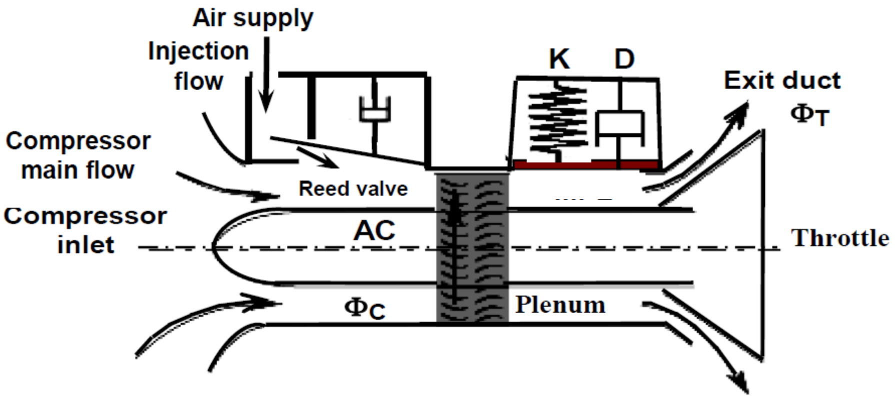


Figure 3: Surge protector

The equation of motion of a reed valve according to Newton's second law can be written as:

$$m_{dv}d^2h_{dv}/dt^2 = G + Fg - (F_v + F_e + F_n) \qquad (4)$$

where m_{dv}, is the discharge reed effective mass, h_{dv} discharge reed displacement, G valve gravity, F_g, gas force acting on the reed, F_v viscous force, F_e elastic force, and F_n is gas damping force. Using Equs. (3, 4), and like to Equ. (2), the compression system model with the air injection trough the reed valve and portable plenum wall is:

$$\frac{d\Phi_c}{d\tau} = B[\Psi_c(\Phi_c) - \Psi_p] - \mu\Phi_c - G\Psi_c(\Phi_c) \qquad (5a)$$

$$\frac{d\Psi_p}{d\tau} = \frac{1}{B}(\Phi_c - \Phi_T) - (F+H)(\frac{d\Psi_p}{d\tau} + f\Psi_p) \qquad (5b)$$

$$\frac{d\Phi_T}{d\tau} = \lambda B[\Psi_p - \Psi_T(\Phi_T)] - \zeta G\Psi_c(\Phi_c) \qquad (5c)$$

$$\frac{d\Psi_c(\Phi_c)}{d\tau} = \frac{1}{\tau}[\Psi_o - \Psi_c(\Phi_c) - h\Psi_p] \qquad (5d)$$

where, $G=\rho l r^2/6m$, b damping constant, ω_n natural frequency, l length of reed valve, $F = (\rho a^2 A_w)/(\gamma K)$, $H = (\rho a^2 C)/(\gamma K)$, $\zeta = b/(2m\omega_n)$, h is a constant depending on the throttle valve opening area, *and* $f = K/D$ (spring stiffness/viscous damping coefficient). The disquiet of the amounts ϕ_c, ψ_p, ϕ_T and ψ_c, Equ. (5) is written in a matrix forms as:

$$\begin{bmatrix} s+\mu-(B-G)\psi_c & B & 0 & 0 \\ -1/B & s(1+F+H)-f(F+H) & 1/B & 0 \\ \zeta G\psi_c & -\lambda B & s+\lambda B\psi_T & 0 \\ \psi_c/\tau & h/\tau & 0 & s\Phi \end{bmatrix} \begin{bmatrix} \phi_c \\ \psi_p \\ \phi_T \\ \psi_c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (6)$$

To deduce surge protector effects, Equ. (6) is written as:

$$s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_o = 0 \qquad (7)$$

Implementation of simulations in the MATLAB environment for an efficient numerical solution and the fourth-order Runge-Kutta method is used for numerical solutions for its high accuracy (Posch, Hopfgartner, Dür, Eichinger, Stangl, & Almbauer, (2018), Yeung, and Murray (1999). The compression system stability and surge point is detected by solve Equ. (7) using the MATLAB program. Back to Fig.2, the system was running stable at a flow coefficient of 0.435. When the flow reduced to 0.428 mild surge cycle appeared and a complete surge cycle at a flow coefficient of 0.412, while a deep surge cycle at rate of nondimensional flow of 0.405. Figure 4 shows system operation at all of the above flow rates under unstable conditions becomes stable operation. Thus, the surge has been suppressed by applying the current control system. A mild surge cycle has occurred at a very low flow coefficient of 0.197 with an enhanced system stable operating range of about 29%.

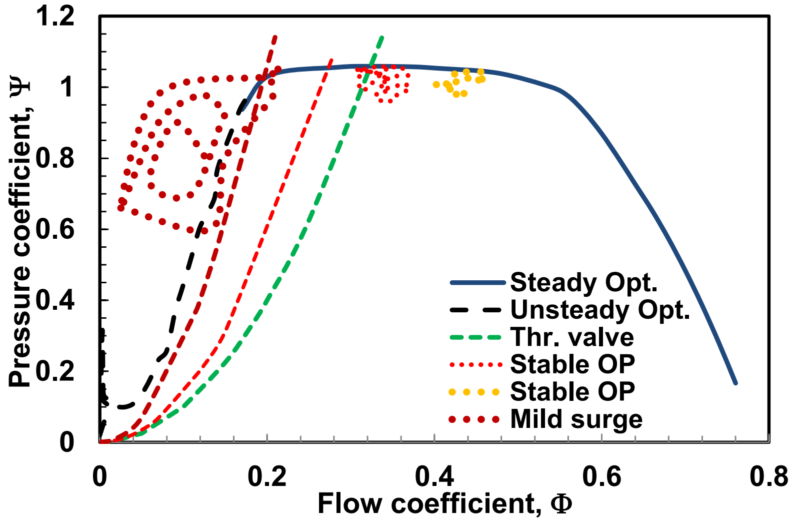


Figure 4: Effect of controller on surge suppression

The air is injected into the inlet of the system in the present model of surge damping by assuming air inoculation act as direct drives of the steady compressor characteristic and the response is relative to the disquiets of the instability amplitude *R* as:

$$\Psi_{ci}(\Phi_c) = \Psi_c(\Phi_c) + K_2 R \Psi_{ca} \qquad (8)$$

Two constants k_o, and k_3 were used to fit the experimental data of (Beheshti, and Farhanieh 2005, Moubogha, and Margalida (2022), Deveaux, Fournis, Brion, Marty & Dazin, (2020), and Nie, Xu, Cheng, & Chen, (2002) in the equality ($\Psi ca = K_o + k_3 \Phi_C$), and convert the compressor into a steady proportional the critical throttle operating point

$$\Phi_T = (h + K_1 \Phi_T) \Psi_T^{0.5} \tag{9a}$$

$$\Psi_c(\Phi_c) = \Psi_p - 0.25 R \partial^2 [\Psi_{ci}(\Phi_c)] / \partial \Phi_c^2 \tag{9b}$$

$$\partial [\Psi_{ci}(\Phi_c)] / \partial \Phi_c = -0.125 R \partial^3 [\Psi_{ci}(\Phi_c)] / \partial^3 \Phi_c \tag{9c}$$

Differentiating Equ. (9) in R and solving the result for dR/dh, the slope of the bifurcation diagram becomes:

dr/dh (at $h=h_c$)=

$$\frac{\sqrt{\Psi_p}}{\dfrac{K_2 \partial \Psi_{ca} / \partial \Phi_c + 0.125 \partial^3 \Psi_c / \partial \Phi_c^3}{\partial^2 \Psi_c / \partial \Phi_c^2} - \dfrac{\Phi_c}{2 \Psi_T} (K_2 \Psi_{ca} + 0.25 \partial^2 \Psi_c / \partial \Phi_c^2)} \tag{10}$$

Equation (10) represents the effect of changing the throttle gain on the compressor characteristics and manifold slope diagram at the critical throttle opening. The result in Fig. 5 shows the effect of air injection on the performance of the compressor system. Air injection leads to an increase in the pressure coefficient at which unstable rotational stop or surge occurs and increases the range of stable operation. About 27% is the improvement in the stable engine operating range where the compressor operates at its highest efficiency, resulting in an improved combustion process in the gas turbine engine.

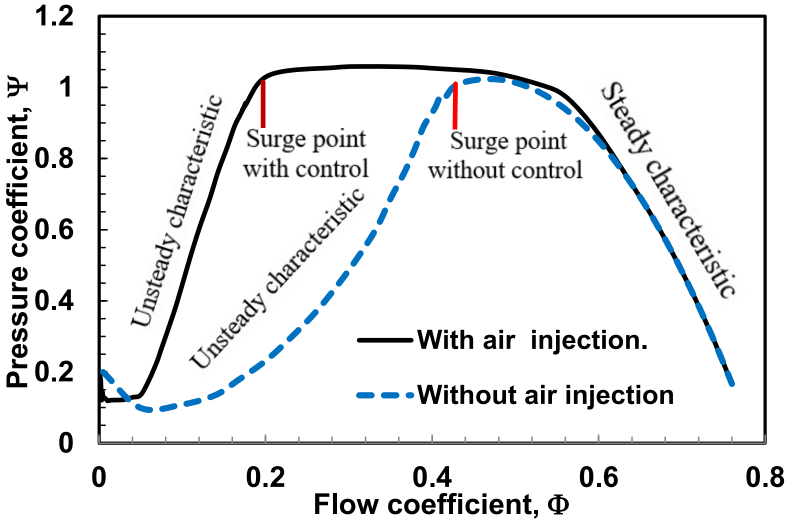
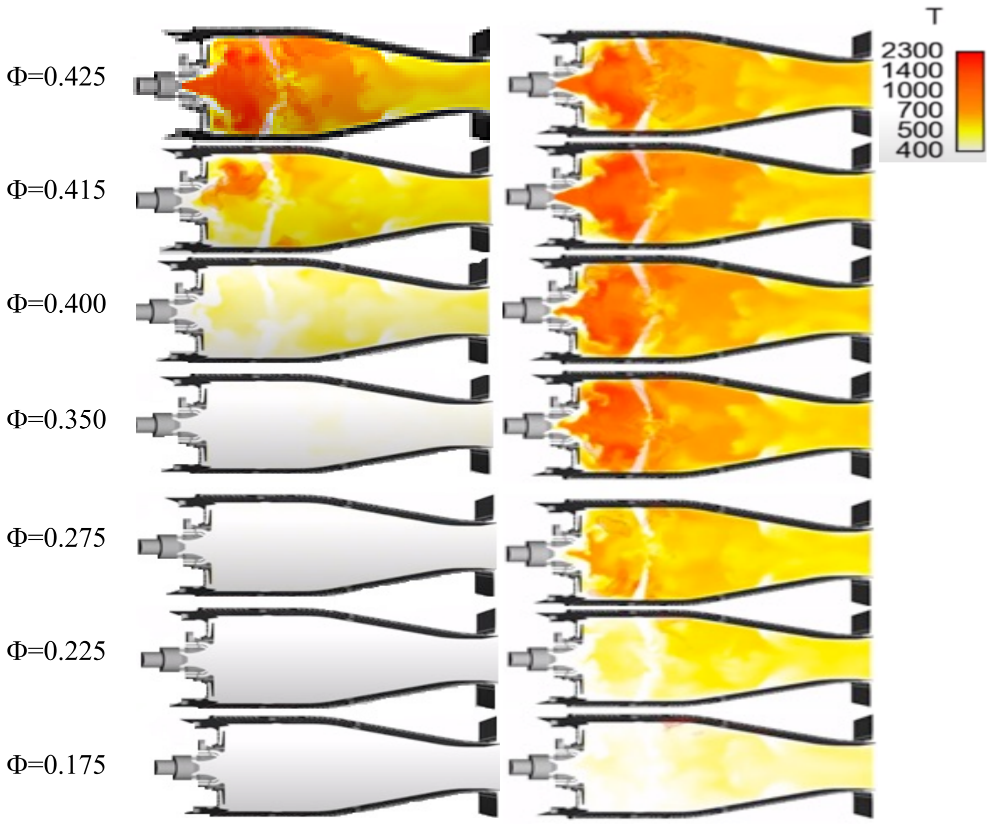


Figure 5: Effect of air injection on system limit of stable operation

Numerical simulation using ANSYS

In this part, a numerical simulation of the mixture particle flow transport inside a gas turbine combustion chamber was carried out using the ANSYS trading software, which tracks the particles using a Lagrangian method (Moubogha, Margalida, Joseph, Roussette, & Dazin, (2021), Jichao, Juan, Shaojuan, Fan, & Hongwu (2020), Jichao, Yang, Juan & Hongwu (2020). The flame is developed in the combustion chamber at different flow rates as shown in Fig. 6. This simulation was able to accurately predict from the beginning of the occurrence of vortices, which were the reason for not completing the process of stopping the combustion due to surge occurrence, at the low flow of the compressor without overheating in the surge process and in the presence of the control of the surge stop. It is clear that the surge has a very large effect on the flame and detonation inside the combustion chamber and the gas turbine stability. With applying the controller and suppressing the compressor surge, the combustion continued and complete combustion occurred until a very low flow rate with a 29% increase in the compressor stable operating range. The results of CFD (Fig.6) give an acceptable agreement with the analytical method that is shown in Figs. 3-5.



a-Without controller b-With controller

Figure 6: Effect of surge suppression on gas turbine detonation

5. Conclusion

This research aims to ensure that the fire does not stop inside the combustion chamber of the gas turbine engine due to the possibility of the compressor working in the presence of the surge, which causes the compressed air to stop coming to the engine. Therefore, a controlled mechanical compensation system with simultaneous air injection through the reed valve was used to suppress the surge phenomenon and to ensure the necessary air flow for completeness and continuity of combustion inside the combustion chamber. The Moore and Greitzer model was developed to include the effects of air injection on axial flow compressor performance and to increase the limit of stable flow operation and surge damping. Also, a numerical simulation of the detonation processes inside the gas turbine combustion chamber was performed using the ANSYS CFX trading software. Flame propagation development and continued explosions in the combustion chamber were monitored at different flow rates. The results show the vibratory plenum wall together with the injection through the reed valve damps the surge with a 29% increase in the compressor stable operating range.

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