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METHODS

Alternative System Design for High Temperature Solid Particle Erosion Wear Problem

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Abstract

In order to simulate the wear behavior of materials subjected to solid particle erosion due to high temperature as well as velocity effect in operating conditions such as power plants and jet engines, ASTM G76 standard is not sufficient and test rig compliant with ASTM G211-14 standard must be put forward. In this context, a test rig, alternative to existing systems where solid particle erosion wear experiments can be performed in compliance with high temperature (~ 700 °C) and particle impact velocity (~ 150 m/s) conditions, has been designed and produced. In order to ensure the widespread use of this test rig, a resistance wire system was used to reach high temperatures of the heating system by achieving a different design solution. In the setup of this design, the perfect gas equation, heating power and ohm laws are also used. In addition, the designs of specimen fixture and particle feeding system, which are the determining parameters in erosion wear tests, have been updated. With the produced test rig; solid particle erosion experiments were carried out using Inconel 718 test specimens at 600 °C temperature, ~ 97 m/s erosive particle impact velocity and three different erosive particle impact angles (30°, 60° and 90°). In the experiments, especially the change of temperature over time was confirmed by the data obtained from both the test rig and the specimens.

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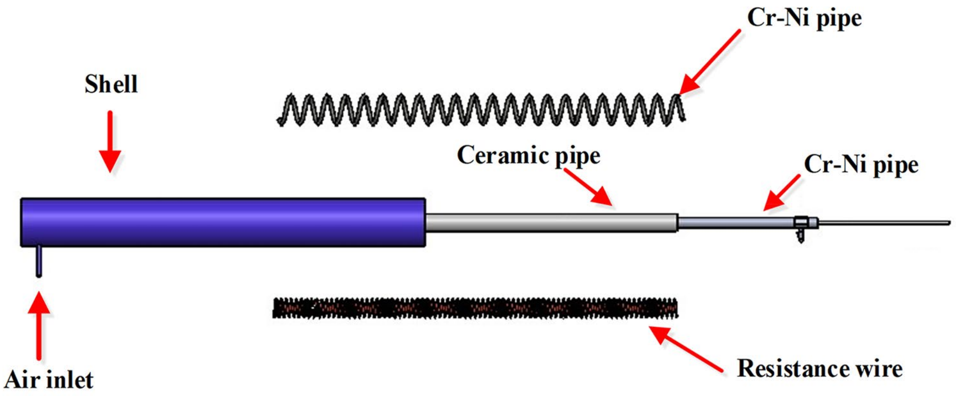
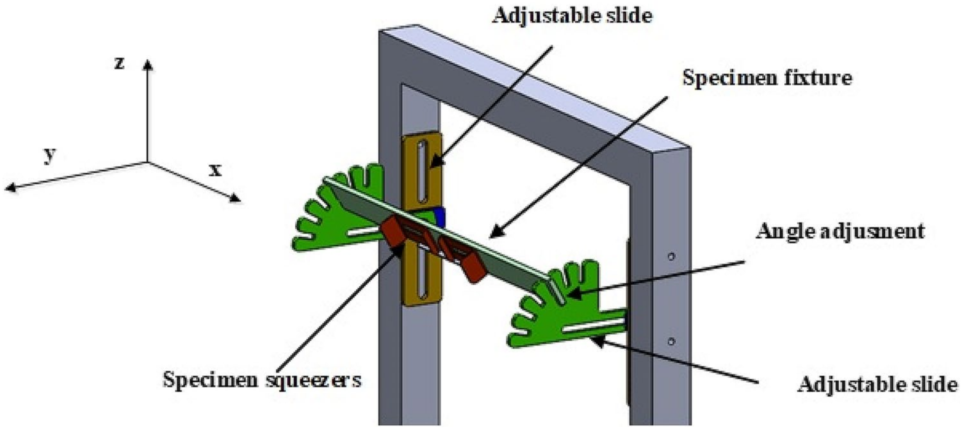
Graphic Abstract





Keywords Alternative engineering design · Design for manufacture · High temperature · Nickel alloys · Erosion wear

1 Introduction

In recent years, research has been needed to deepen the production of experimental devices in order to examine the wear behaviours of materials exposed to solid particle erosion in high temperature conditions in laboratory conditions, and studies are continuing to develop experimental test rig [1–3].

Common methods for performing solid particle erosion (SPE) wear in laboratory conditions; erosive particles are accelerated by a gas or liquid, or circular movement is used to achieve the impact velocity of erosive particles. Among these, in the method where the erosive particle is accelerated with a gas or liquid, erosive particles are placed in a nozzle and the particles are accelerated by the flow of gas or liquid passing through the nozzle. Accelerated erosive particles are impacted against the target material surface, which is at a certain angle and distance from the nozzle tip. In this method, called gas jet, erosive particles are accelerated with gas (usually air) or liquid (oil or water) as a carrier. It is the internationally accepted standard ASTM-G76 [4], which defines the test method in which air is used as the carrier of erosive particles in the gas jet method.

ASTM-G76 [4] standard is widely used in room temperature SPE tests and SPE tests can be performed at an impact angle of 15°–90° and low impact speeds such as 15–75 m/s using Al_2O_3 erodent in size 50–450 µm [5–8]. Although this standard provides ideal results at the specified intervals, it is insufficient to represent the SPE event occurring in systems such as power plants, jet engines and gas turbines that require high temperature and velocity. In gas turbines, especially in parts used as combustion chamber elements and the driving force materials of the aircraft, SPE wear results in more destructive process along with high temperature. The unit gas turbine production used in the aviation industry is estimated to be 244,619 engines worth $1.4 trillion in 2019–2033 [9]. Similarly, gas and steam turbine unit production used in industrial and maritime transportation for 2019–2033 is projected to be 26,202 engines worth $308.1 billion [10]. Therefore, considering these estimates, it is stated that the test rigs for high temperature solid particle

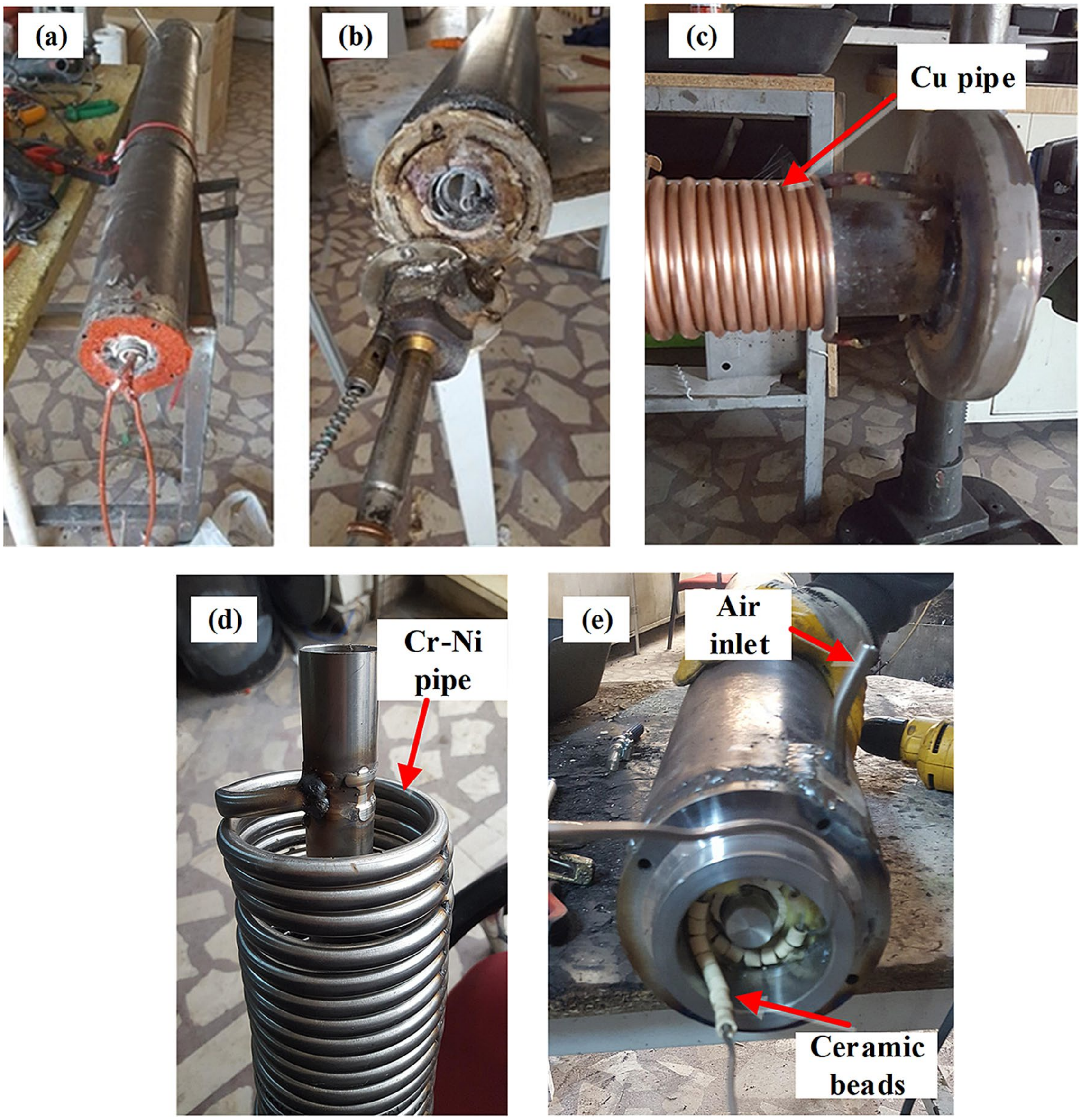


Fig. 1 Heating system manufacturing processes with resistance wire; **a** system insulator electrical connection detail, **b** deformation occurring in the system after electrical input, **c** transition to use Cu pipe for revision in the system, **d** final revision of the system with Cr–Ni pipe connection, **e** system final version with ceramic bead casing

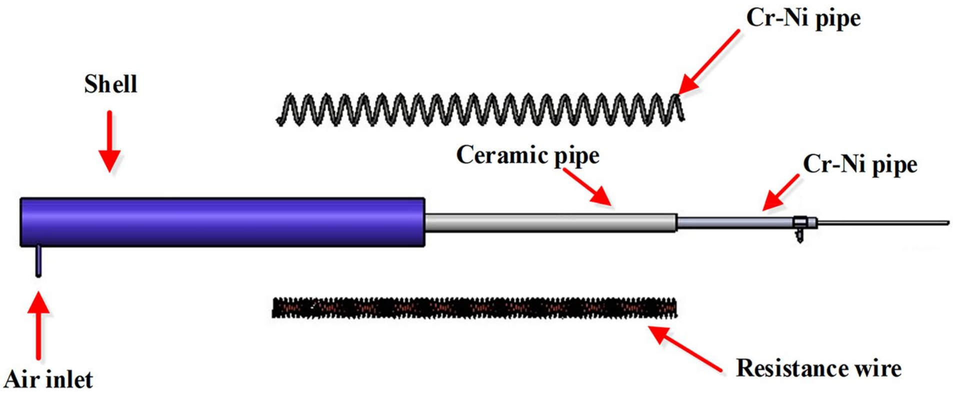


Fig. 2 Exploded view of heating system 3D drawing

erosion (HTSPE) wear tests can be performed will be of serious importance. Within the framework of this basic issue, it was concluded that the need for test rig compatible with the standard ASTM_G211-14 [11] this needs reworking as it reference the temperature as well as velocity. Also, the air is heated and accelerated by heating particles with the resistance wire, which will create an alternative solution in the heating system. The production of the test rig, where the temperature control (specimen, air and erosive particle) is provided with a resistance wire, the air flow rate is determined, and the erosive particle impact angle can be adjusted, has been completed. After that experiments at high temperature and velocity values have been made. As a result of this test rig, the effectiveness of the temperature control has been demonstrated at 600 °C, with the erosion rate results in three different erosive particle impact angles and constant particle impact velocity.

2 Alternative System Design Components

2.1 Heating System Design

In order to heat the air to the desired temperature, the ideal gas law has been used on the heating power calculation as a result of the necessity of determining the heating power depending on the air flow and air velocity.

$$P = \rho \times R_{\mathrm{air}} \times T \tag{1}$$

In this equation; P is the air pressure (bar), ρ is the density of the air (kg/m^3), R_{air} is the gas constant of air (kJ/kg K) and T are expressed the temperature (°K) of the air. In the Eq. (1), the air pressure is accepted as 1.5 bar and the density of the air is determined as 0.445 kg/m^3.

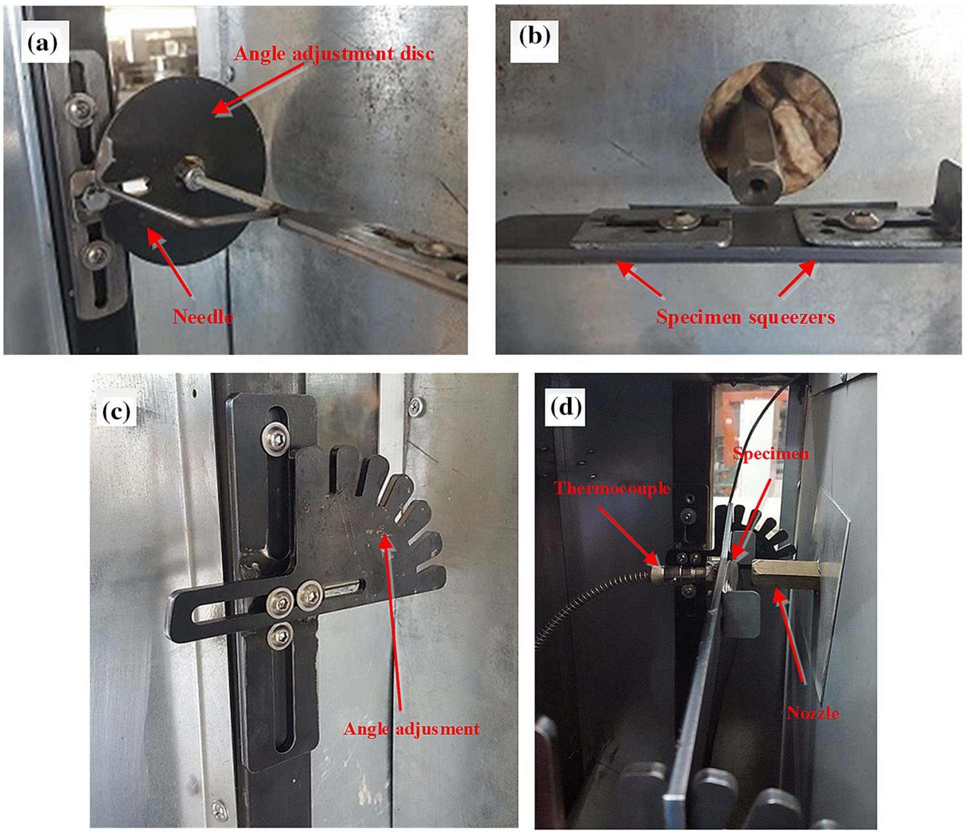
$$\dot{V} = \vartheta \times A \tag{2}$$

The volumetric flow of air (m^3/s) was calculated by using the Eq. (2). In the Eq. (2), ϑ is the air velocity (m/s), A is the nozzle cross-section area (m^2) is expressed and the data of the nozzle diameter 5 mm and air velocity of 300 m/s planned to be used in the experiment set are taken as reference.

$$\dot{m} = \rho \times \dot{V} \tag{3}$$

The mass flow rate of the air was theoretically calculated 2.62×10^{-3} kg/s by the Eq. (3). The basic thermodynamic equation stated in the Eq. (4) was used in determining the heater system power that would provide alternative difference in design. As a result of the theoretical engineering calculations, the design of the heater power (W_{heat}), which

Fig. 3 Specimen fixture prototypes; **a** sliding angle adjustment disc, **b** sliding specimen holding apparatus, **c** precision impact angle adjustment, **d** control of the specimen temperature with a thermocouple



will reach 900 °C air temperature, has been revealed from Eq. (4).

$$Q + W_{\text{heat}} = \dot{m} \times \left[C_p \left(T_2 - T_1 \right) + \left(\frac{\vartheta_2^2 - \vartheta_1^2}{2 \times 1000} \right) \right] \tag{4}$$

In the theoretical calculations, the system was considered adiabatic ($Q=0$). After calculations, it was determined that the system needed ~ 5 kW heater power by including systemic losses and efficiency status. The calculations were made according to the fact that the air at room temperature can reach 900 °C temperature using a resistance wire. In order to calculate the diameter and length of the resistance wire, which is planned to be used as an alternative heating system, the electrical resistance value was determined primarily by using the Electrical Power equation through Ohm's Law. Cr–Ni was used as the material of the resistance wire, which is the basic parameter in the design, and it was revealed that the diameter and length data of the resistance wire required ~ 1.5 mm wire diameter and ~ 15.6 m wire length, respectively.

As a result of this theoretical engineering data, the manufacturing process was started in order to reach the desired temperature and the prototypes revealed in this process are described in Fig. 1. In this prototype, the heated air had damaged the protective pipe in the furnace and the resistance wire. The resistance wire was oxidized, and exfoliation had occurred on the selected protective pipe material surface. Therefore, design revisions were deemed necessary and a new system design was made for the heater. As a result of this new design, the targeted temperature (~ 700 °C) was reached.

In order to provide the best heat transfer from the heated resistance wire, a design had been put forward to allow heating air by passing through a pure copper pipe which has a heat conduction coefficient of 386 W/m C and a melting temperature of 1083 °C. In this design, the heated air reached ~ 700 °C temperature, but the copper pipes melted at this temperature in case of long-term operation. After this design was unsuccessful, it was turned into a spiral network by using Cr–Ni pipes instead of Copper pipes to make more stable air temperature in long-term operation. Ceramic beads are placed on the resistance wire in order to ensure its electrical insulation between the Cr–Ni pipe and the resistance wire. In Fig. 2, an exploded view of the 3D computer aided drawing of the final design of the heating system is given.

In the preliminary experiments carried out as a result of the manufacturing process, where the basic desire and the design expectation were put forward with this design, it was observed that the air temperature can reach up to 700 °C and keep this temperature steadily without encountering

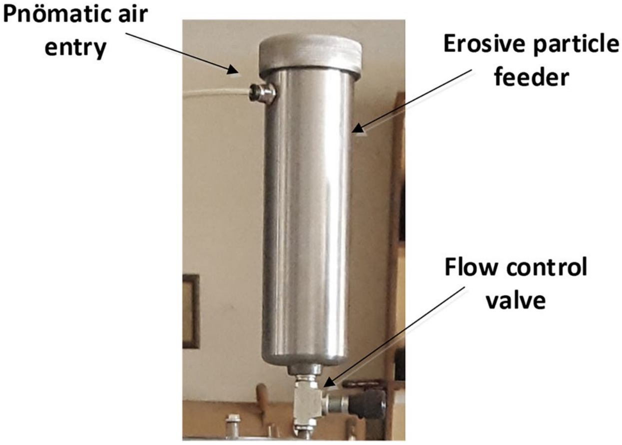


Fig. 5 Particle feeding unit

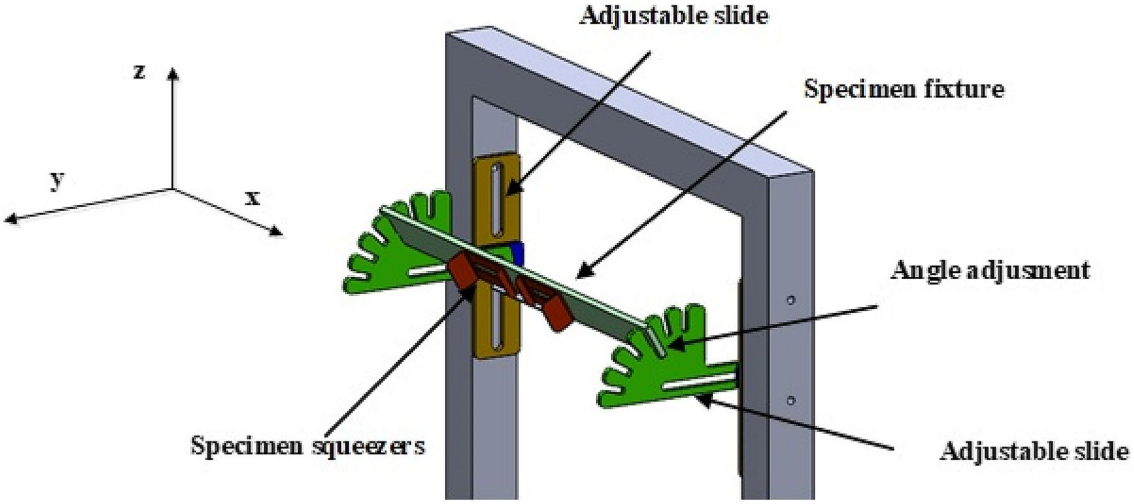


Fig. 4 Specimen fixture 3D drawing

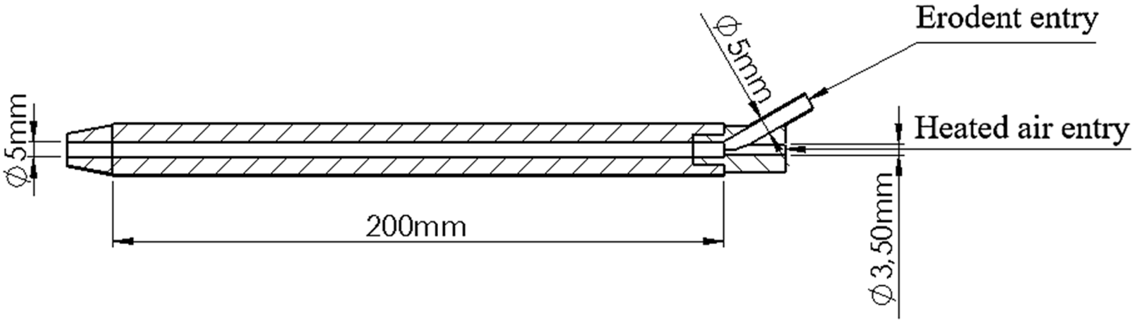


Fig. 6 2D drawing of the nozzle design

any problems. The specified temperature was measured in line with the information from thermocouples and read digitally on the PLC screen. As a result, the production of an alternative system with easier manufacturing and low cost design, in which the incoming air from the compressor can be heated in accordance with the international standard of ASTM G211-14, has been completed and experiments have been carried out at different temperatures and higher impact velocities.

2.2 Specimen Fixture Design

It is extremely important to rigidly connect the specimen to the fixture when performing erosion wear tests. Otherwise, the clearance between the specimen and the fixture and scatter of specimen during the impact of the erosive particles coming out of the nozzle will negatively affect the wear scar that will occur after the SPE wear. Therefore, a specimen fixture design requirement has been made that will allow the specimen to be aligned with the nozzle and allow the specimen to stand rigidly in the fixture. Also, lateral and horizontal standoff distance could be adjusted.

In addition, it is important to adjust the impact angle, one of the most influential parameters in erosion wear tests, and one of the important factors in determining whether the specimen is ductile or brittle material. As it is difficult to obtain same specimen size in erosion wear tests, an alternative was also considered in the specimen fixture design, in which different sizes of specimens can be fixtured. The basic design parameters are determined as the fact that the specimen fixture is rigid, the specimens of different sizes can be fixtured, the angle of impact can be adjusted, the specimen can be mounted and disassembled easily, and the distance can be adjusted aligned with the nozzle.

The prototypes shown in Fig. 3 have been manufactured and the final design has been shaped after the fixture designs that have been created with the prediction of these design parameters.

The features such as the connection of the specimen to the fixture with the help of a slide, no gap between the slide and the specimen and enabling the connection of specimens of different thicknesses enabled this design to be selected. With this system, the possibility of free mobility to ensure that the specimen aligns with the nozzle is also added to the specimen. Consequently, it is provided to make the specimen fixture easily removable and pluggable from the test rig (Fig. 3c, d) depending on the demand for the ideal expectation that the compact and easy control was aimed at. As a result, the specimen fixture is placed in slotted sections at the desired angle and experiments can be performed. The slotted precision angle adjustment used in this system have been made independent from the bolt adjustment and have made the control of 15° impact angles more stable. Also, in this system, the specimen can move in three axes and with the angle adjustment system it can rotate in the fourth axis. In order to measure the temperature of the specimen that will be exposed to HTSPE erosion, a hole is drilled behind the region where the specimen is placed to contact the thermocouple. In this way, it is provided to interpret the temperature effectiveness on the specimen. In Fig. 4, 3D drawing of the design of the specimen fixture is shown.

2.3 Particle Feeding Unit Design

Volumetric feeding unit was preferred in the choice of particle feeding unit, and the ability to use different erosive particles (iron powder, alumina, quartz etc.) in this method has highlighted it [12, 13]. The main criterion in the particle feeding unit design, is the prevention of variable amounts of abrasive particle flow. It is aimed to adjust the pneumatic valve on–off speed from the PLC system by connecting a pneumatic on–off valve to the particle feeder system first. However, the blockage problem occurring in the pneumatic valve with this system has revealed the flow of irregular particles. It was determined that a solution would be found by manually adjusting and controlling the particle feeding process with the hydraulic flow control valve before the

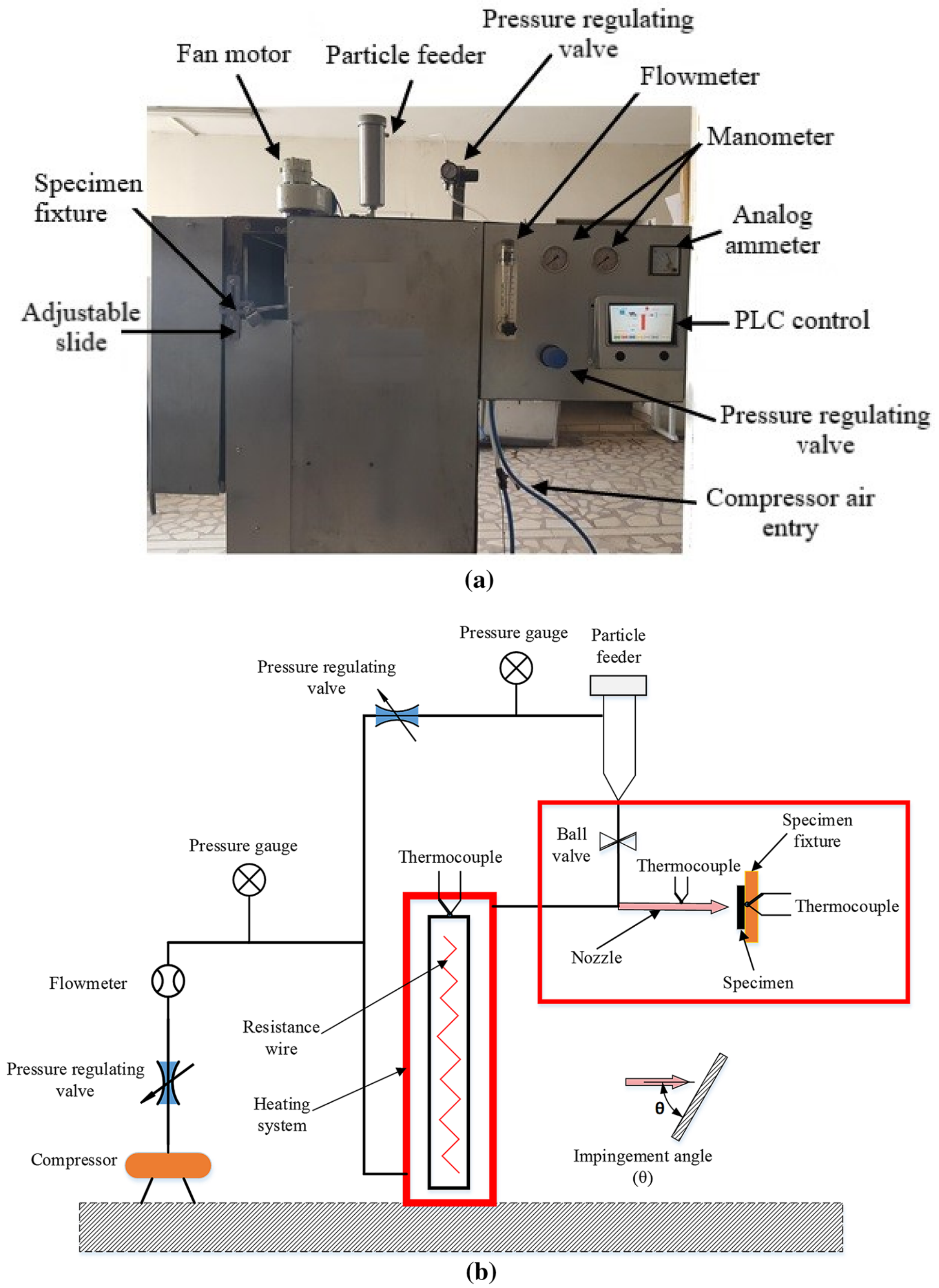


Fig. 7 HTSPE test rig; **a** photo view, **b** schematic representation

Table 1 Specifications of high temperature solid particle erosion facility

Parameters	HTSPE
Test section air temperature (°C)	21–700
Particle impact angle (°)	15–90
Particle impact velocity (m/s)	10–150
Particle size (µm)	25–500
Specimen size (max.) (mm)	50 × 50

experiments, and the process was carried out smoothly with the system in Fig. 5.

2.4 Nozzle Design

Based on the theoretical calculations made in the heating system design, literature studies [14–17] have been examined in detail to determine the nozzle diameter and size, and in order to determine the nozzle size that can provide a laminar flow after the combination of heated air and erosive

Table 2 Values measured after the double disc method experiment

Experiment no.	*S* distance (mm)	*L* distance (mm)	*r* diameter (mm)	Velocity (m/s)
1	5.8	12	44	90.8
2	5.4	12	43	95.4
3	5.3	12	46	103.9
Average impact velocity (m/s)	–	–	–	96.7
Standard deviation	–	–	–	6.7

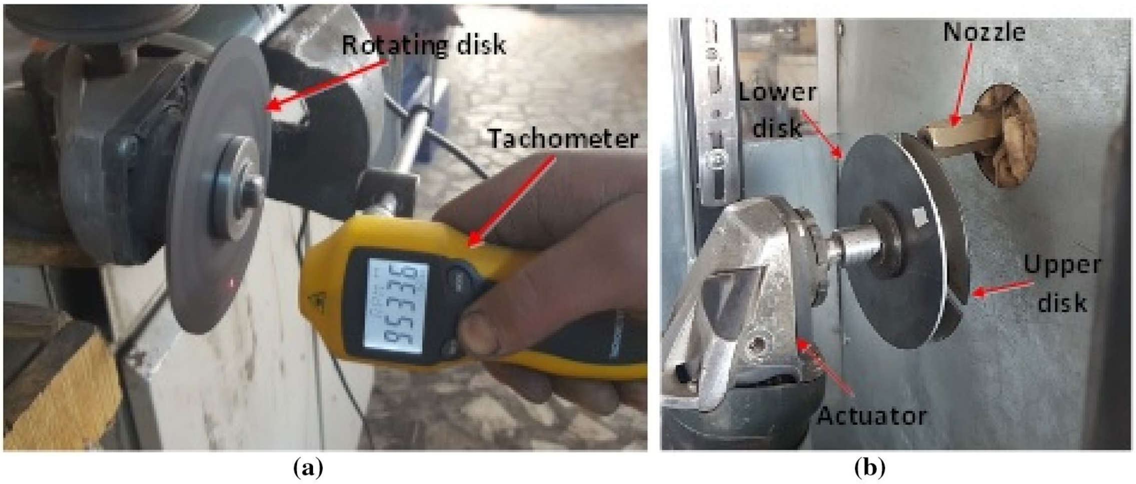


Fig. 8 Impact velocity measurement with double disc method; **a** measuring the rotational speed of the disc with a tachometer, **b** creating scars by the movement of the lower and upper discs

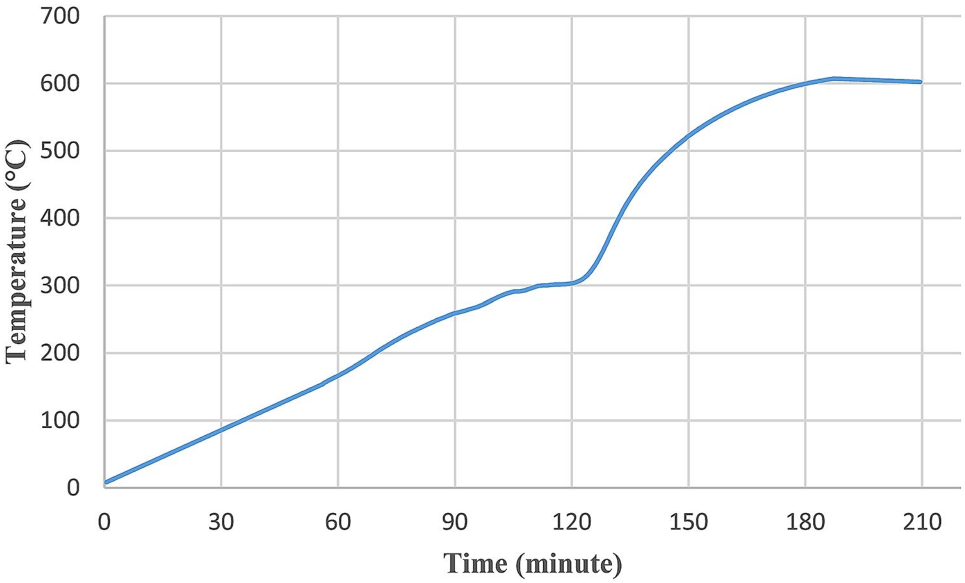


Fig. 9 Time required for the specimen to reach a temperature of 300 and 600 °C (6 m^3/h air flow; inconel 718 super alloy specimen)

particles in the nozzle; a design with a nozzle diameter of 5 mm and a length of 200 mm was manufactured. It has been decided to use 304 quality stainless steel (X5CrNi18-10) material for the nozzle to withstand high temperatures and erosive particles. Figure 6 shows the 2D manufacturing picture of the designed and produced nozzle.

With the completion of the heating system, specimen fixture, particle feeding and nozzle designs that provide

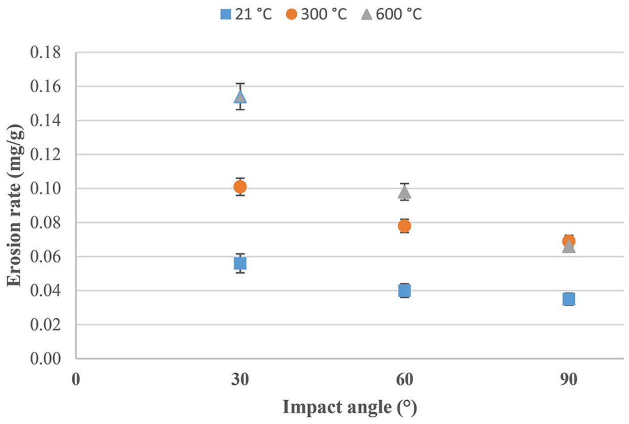


Fig. 10 Change of the impact angle—erosion rate graph of three temperature values

alternative features and differ from the existing heating systems, the photo image and schematic of the HTSPE test rig is described in Fig. 7a, b. In Table 1, it is given the test rig specifications.

In the HTSPE test rig, three thermocouples were used to measure temperatures at the specimen, at nozzle inner surface and inside the heating system, allowing the temperature data to be checked from different points and air temperature stability. With the help of the fan motor used in the test rig, the dust that may occur during the experiments was prevented from dispersing into the working environment and discharged to the outside environment with the help of a chimney. In addition, with the flow meter, the air entering the system can be adjusted in l/min, the pressure entering the system can be controlled with the pressure regulating valve, the current intensity value (amper) drawn by the system during the operation of the heating system with the analog ammeter, the system can be increased to the desired temperatures by the control of the PLC system.

2.5 Erodent Impact Velocity Measurement

The double disc method has been used to determine the erosive particle impact velocity, and in addition to three experimental measurement data to determine the impact velocity;

$$\vartheta = \left[\frac{2\times\pi\times n}{60}\right]\times\frac{L}{S}\times r \tag{5}$$

By using the equation, ~ 97 m/s average impact velocity data, which are planned to be used in erosion wear tests, have been reached. Repetitive velocity tests measurements details are given in Table 2. The pictures of the measurements made in order to obtain the velocity data of the double disc method equation are given in Fig. 8. It has been determined that the uncertainty rate between the scars varies between 3 and 7%, and it has been concluded that an uncertainty of approximately 8–10% represents the acceptable limit in measurement with this method [18].

3 Result and Discussion

Solid particle erosion tests of superalloy materials were carried out with the test rig in which the variability of the impact angle can be provided, in which erosive particles of different sizes and properties compatible with high temperature and velocity conditions. It was primarily aimed that the alternative test rig, designed and produced and compliant with the ASTM G211-14 standard, can reach 700 °C air temperature values, and the temperature–time graph for obtaining this temperature is given in Fig. 9. When this graph is examined, the heating system entered the regime after a certain period, targeting 300 °C first, and this temperature value was reached through the thermocouple on the nozzle. In order to carry out the experiments by increasing the temperature capability of the test set to 600 °C, a value of 600 °C was obtained at the nozzle outlet temperature and it was ensured that the experiments could be carried out with Al_2O_3 erosive particles with an average diameter of 200 µm at an impact velocity of approximately 97 m/s. In the experiments, 100 g of erodent was used at a flow rate of 32 g/min. It is aimed that this change in gas temperature does not affect the sample surface temperature directly and the experiments are primarily interpreted according to the air temperature parameter. That is, the gas temperature was studied independently of the sample temperature. Therefore, in case of need, the variation in temperature of the sample can be used as an experiment parameter. As a result, it has been proved that the experiments of room temperature, 300 and 600 °C can be carried out efficiently without encountering any problems in the test rig with 700 °C upper temperature limit.

3.1 Steady State Erosion

Inconel 718 test specimens were subjected to tests at three different nozzle exit temperatures (21, 300 and 600 °C) at three different impact angles (30°, 60° and 90°) and the results obtained in constant velocity and erosive effect are given in Fig. 10. Three repetitions were used to obtain these graphics, and when the error bars given in the graphic were examined, the erosion rate was calculated depending on the number of erosive particles used, where maximum erosion wear occurred at a 30° impact angle.

When the ploughing and cutting effect occurred on the surfaces of the test specimens under the effect of the erosive particle impact angle of 30° was evaluated, the results showed compatibility with the ductile materials in the literature when the tendencies of ductile, semi-ductile and brittle materials were compared [19].

In these experiments where the efficiency of the test rig on temperature was tried to be determined, the temperature dependence of the test rig was determined as ± 5% °C by ensuring the sensitivity of the temperature to remain constant throughout the test period.

When the temperature effect is combined with angular impact, and the test parameter is changed towards the vertical impact angle of 90°, the ploughing effect has turned into a form of incubation on the specimen surface. This situation showed that when the temperature capabilities of the test rig are combined with the velocity efficiency, it was concluded that consistent results of erosion wear can be made with this test rig.

4 Conclusions

Within the scope of this study, a test rig was designed and produced in which solid particle erosion wear tests can be carried out under laboratory and high temperature conditions and complies with the internationally accepted ASTM G211-14 standard. The High Temperature Solid Particle Erosion test rig has taken its final shape in five different designs, and several different design revisions have been made in determining the specimen fixture and creating the particle feeding unit. With this test rig, it was ensured that the turbine engine components used as basic components in gas turbines and materials subjected to thermo-mechanical loads operating in high-temperature conditions, can be tested for erosion wear tests.

In the heating system of the test rig, using the perfect gas equation, the density of the heated air was found, and the heating power calculation was made.

The length and diameter of the resistance wire used in the heating system were determined using Ohm's law.

Fixture has been designed so that the erosive particle impact angle can be changed at 15° impact angles and the erosion scar diameter does not exceed 2 cm at 90° erosive particle impact angle.

As a result, the test rig with the following capabilities was produced; specimen test temperature (21–700 °C), particle impact velocity, angle of impact (15°, 30°, 45°, 60°, 75°, 90°), erosive particle size (25–500 μm) and test specimen properties (all high-strength and coated specimens) and specimen sizes (max. $50 \times 50\ \mathrm{mm}^2$).

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Compliance with Ethical Standards

Conflicts of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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