ENGINEERING GRAPHICS APPLIED TO THE ASSEMBLY PROCESS OF A SINGLE-CYLINDER HIGH-PRESSURE STEAM ENGINE WITH A CORLISS VALVE GEAR

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Received: 17/07/2025 – Reviewed: 01/08/2025-- Accepted: 21/08/2025 - DOI: https://doi.org/10.52152/D11491

To cite this article: ROJAS SOLA, José Ignacio; SANCHEZ GARCIA, Santiago. ENGINEERING GRAPHICS APPLIED TO THE ASSEMBLY PROCESS OF A SINGLE-CYLINDER HIGH-PRESSURE STEAM ENGINE WITH CORLISS VALVE GEAR. DYNA. Vol. 101, n.1, pp. 31-36. DOI: https://doi.org/10.52152/D11491

ABSTRACT:

This paper presents a detailed description of the assembly process for the different components of a historical invention, specifically a high-pressure single-cylinder steam engine with a Corliss valve gear designed by Arnold Throp, as published in the «Model Engineer» magazine in 1982 and whose original plans were reproduced by Julius de Waal in 2018. Autodesk Inventor Professional 2024 was employed to create a coherent and functional 3D CAD model that incorporates all components described in the reproduced plans. However, challenges arose due to missing dimensions in the available plans and certain inconsistencies, necessitating the formulation of hypotheses regarding the geometries of some elements and the estimation of their dimensions. Additionally, a series of dimensional, geometric, and kinematic constraints (degrees of freedom) were applied to ensure a proper assembly without component overlaps. Furthermore, a limitation was encountered when using Autodesk Inventor Professional for assembling the invention: the software does not take into account for the deformation of components made of elastomeric materials such as the drive belt. Finally, once the 3D CAD model was obtained, graphical documentation of the invention was produced (including assembly plans and detailed perspectives), and a simulation of the invention's operation was conducted, resulting in a virtual recreation of the steam engine. This has provided new insights that facilitate a more comprehensive understanding of the invention and its dissemination to the wider community.

Keywords: **Geometric modelling, assembly process, Autodesk Inventor Professional, single-cylinder high-pressure steam engine, Corliss valve gear.**

FUNDING

The research presented in this work was made possible thanks to a collaboration grant with the Department of Engineering Graphics, Design and Projects of the University of Jaen, obtained in the 2024 call of the Ministry of Education, Vocational Training and Sports of the Government of Spain.

1. - INTRODUCTION

The steam engine has been a historical invention frequently used to generate motive power [1]. It is, in essence, a heat engine that leverages the gradient between the input and output temperatures of steam, converting thermal energy into mechanical energy capable of driving various devices or being implemented in diverse modes of locomotion, such as ships or trains.

Furthermore, they have been widely developed since the 18th century, incorporating various technological improvements to optimize their performance in different productive sectors [2]. Consequently, they have been extensively studied from different perspectives, such as engineering graphics [3] or mechanical engineering [4], among others.

This paper follows a line of research focused on the study and analysis of the design of those historical inventions that marked a milestone in the development of the steam engine, through the incorporation of different technological innovations. One such machine is the subject of this research, which primarily aims to document and facilitate the understanding of the assembly process for a single-cylinder high-pressure steam engine with a Corliss valve gear. This will be achieved through 3D CAD modeling, serving as a foundational resource for future educational and engineering applications.

George Henry Corliss [5-7] was an American engineer (1817-1888) who contributed outstandingly to the efficiency of these steam engines, in particular, acting on the design of valves and regulators. Its invention was the subject of various patents [8-10] that

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

incorporated successive innovations. It consisted of a design featuring rotary valves with variable synchronization, which offered superior thermal performance compared to other stationary steam engines. This latter observation serves as the justification for conducting a study of this historical invention.

The Corliss steam engine with its distinctive valve gear is extensively documented in numerous period bibliographic references. These sources offer insights into the origin and development of the Corliss valve mechanism in relation to preceding technologies [11], provide practical handbooks for operation [12], present a general overview of steam engines including an analysis of Corliss engines [13], detail the assembly, adjustment, and maintenance of Corliss engines and their valve mechanisms [14], and delve into the theory and practice of designing valve mechanisms for steam engines with a comprehensive analysis of the Corliss valve gear [15].

Specifically, this research focuses on the study of the design of a single-cylinder high-pressure steam engine with a Corliss valve gear designed by Arnold Throp and published in the 'Model Engineer' magazine in 1982 [16,17], showing the linkage system that actuates the intake and exhaust valve system, and that configure the Corliss distribution.

To facilitate the aforementioned assembly process, this research leverages engineering graphics, a discipline whose significant importance is highlighted in [18]. Engineering graphics is considered fundamental within the engineering domain, essentially serving as the visual and technical language employed to conceive, develop, and communicate engineering projects. Among the most frequently employed engineering graphics techniques currently applied to industrial heritage conservation and restoration projects are technical drawing [19-21], 3D modeling and virtual reconstruction of industrial buildings and/or machinery [22-24], photogrammetry and laser scanning [25-27], Building Information Modeling (BIM) [27,28], Geographic Information Systems (GIS) [29], augmented reality [30], virtual reality [27,31], and region-wide projects incorporating these technologies [32].

Thus, what this research seeks is to show the different stages followed in the assembly process of this historical invention, as a preliminary step to obtaining its virtual recreation and to carry out analyzes from the approach of mechanical engineering. Therefore, previously, each and every one of the components of this invention has been modeled, obtaining a reliable 3D CAD model, as well as its corresponding graphic documentation. This modeling process has followed the principles of historical rigor, authenticity and scientific transparency of the Seville Principles document [33] on virtual archeology and the London Charter [34] on computer-assisted visualization of cultural heritage.

Therefore, it is an original and innovative work, which represents a significant advance in the knowledge of the technological innovations of these steam engines. It presents a distinct approach compared to focusing on the thermodynamic cycle within the cylinder [35] or the physical realization and verification of the machine's design [36]. This distinctiveness stems from its detailed mechanical explanation of the engine's operation, achieved through a comprehensive exposition of its 3D CAD model assembly.

2. - MATERIAL & METHODS

The material for this research was based on plans reproduced by Julius de Waal in 2018 [37], drawn in the decimal metric system, of an invention designed by Arnold Throp and published in the «Model Engineer» magazine in 1982 [16,17]. These plans present the dihedral projections of each element comprising the invention, allowing for the creation of a 3D CAD model of the final assembly after applying the corresponding constraints between elements. Furthermore, to ensure correct assembly, certain degrees of freedom of each component, which are influenced by the type of constraint (geometric, dimensional and kinematic), were restricted. In this way, a functional and coherent 3D CAD model is obtained, which has an appropriate relative movement between elements, verified by means of an interference analysis.

The modeling and assembly processes were carried out using Autodesk Inventor Professional 2024 software [38]. Thus, once the 3D CAD model of the steam engine was obtained, it was possible to obtain its graphic documentation (assembly plans, subassembly plans, detail perspectives and exploded perspective). In addition, some drawbacks were found in these plans, hindering the 3D CAD modeling process.

Essentially, these drawbacks consisted of the absence of dimensions in some components, which had to be deduced from the knowledge of the location of the component in the assembly, or had to be resized, due to geometric interferences in the assembly process. Several significant inconsistencies were identified in the engineering drawings. For instance, the total length of the frustum for the cylinder exhaust valve bonnet was not specified in its dedicated blueprints, necessitating its derivation from the comprehensive exhaust valve schematics. Similarly, contradictory dimensions were observed in the intake valve drawings concerning the steam intake valve lever. Specifically, differing thicknesses of 4 mm and 5 mm, respectively, led to geometric superimposition during assembly.

Likewise, a virtual recreation was made where its operation is shown, in a clear and understandable way, thanks to the Inventor Studio module incorporated in the aforementioned software. However, this software does not consider the deformation of

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

components made with elastomeric materials, visible in the drive belt, which produces a limitation in this virtual recreation. For the steam engine to function optimally, three distinct origins of motion have been introduced to mitigate the aforementioned drawbacks. These movements are primarily observed in the rotation of the crankshaft and the governor, establishing a rotational relationship between the pulleys where the drive belt is located. Furthermore, due to the independent operating mechanism of the Corliss valves, a motion restriction was necessarily applied within the control unit. The model can also be validated through the developed virtual recreation, which demonstrates the operating principle of the historical invention. This approach is necessary because no physical prototype exists for validating the 3D CAD model. Finally, the methodology applied in this research has been explained in detail in other articles on relevant historical inventions [39,40].

3. - RESULTS & DISCUSSION

The modeling process of the invention is notable for its complexity, reflected in the large number of elements that comprise it, specifically, 120 components. In figure 1, two axonometric perspectives are shown that illustrate the front and rear of the complete assembly.

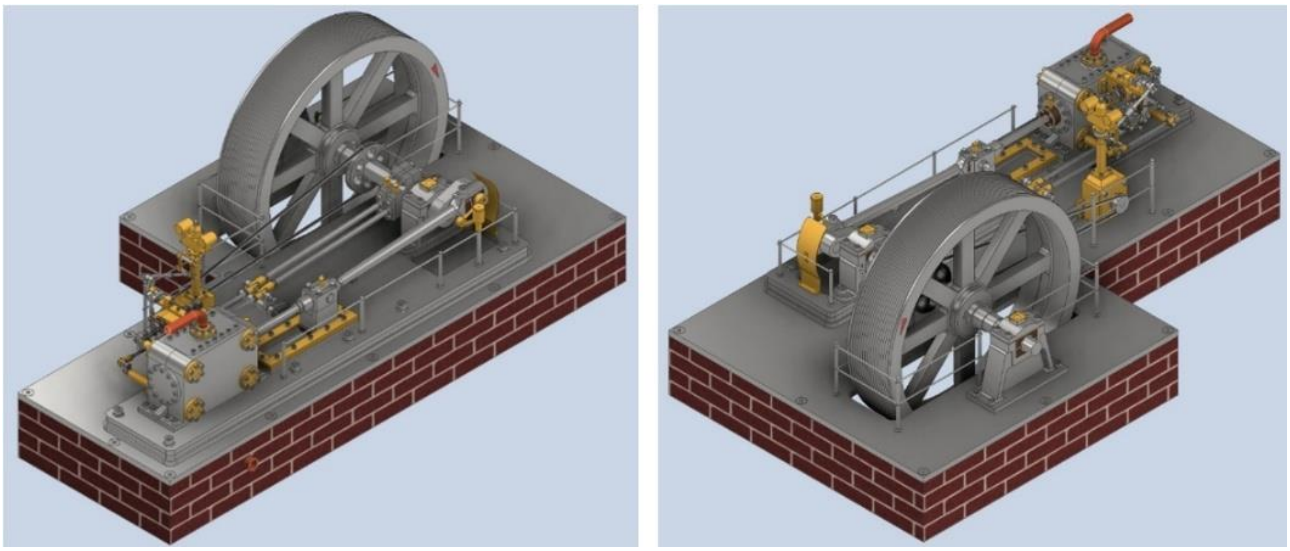
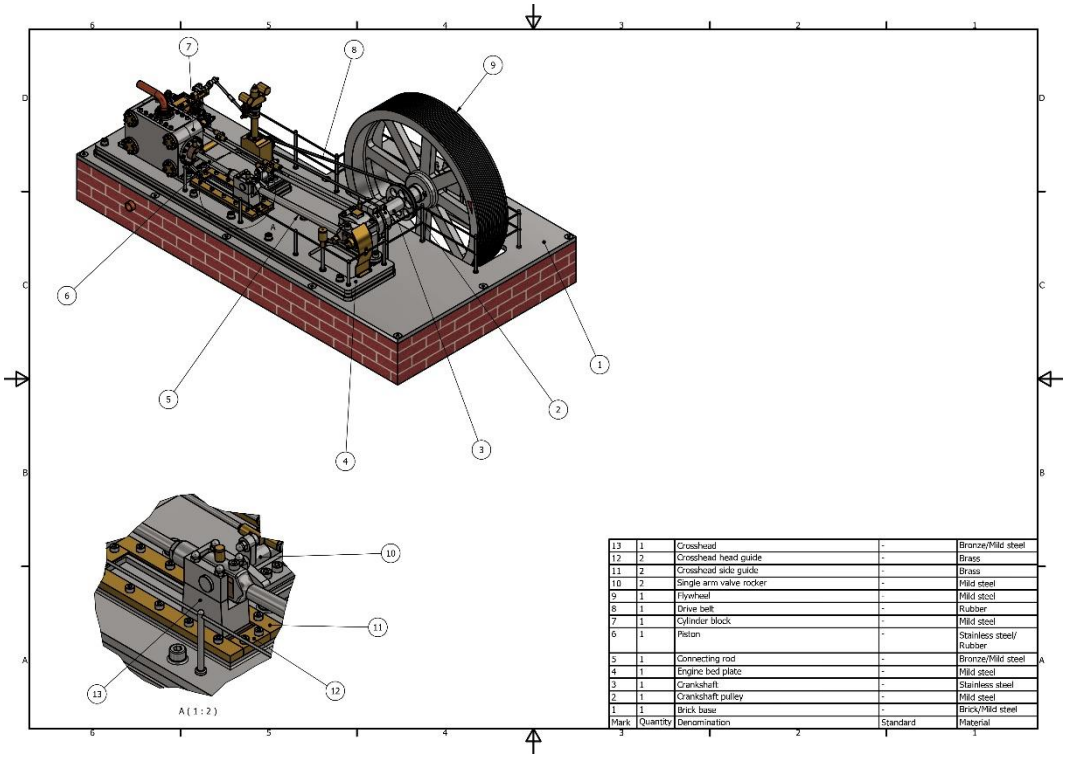


Fig. 1. Axonometric views of the invention: front view (left) and rear view (right)

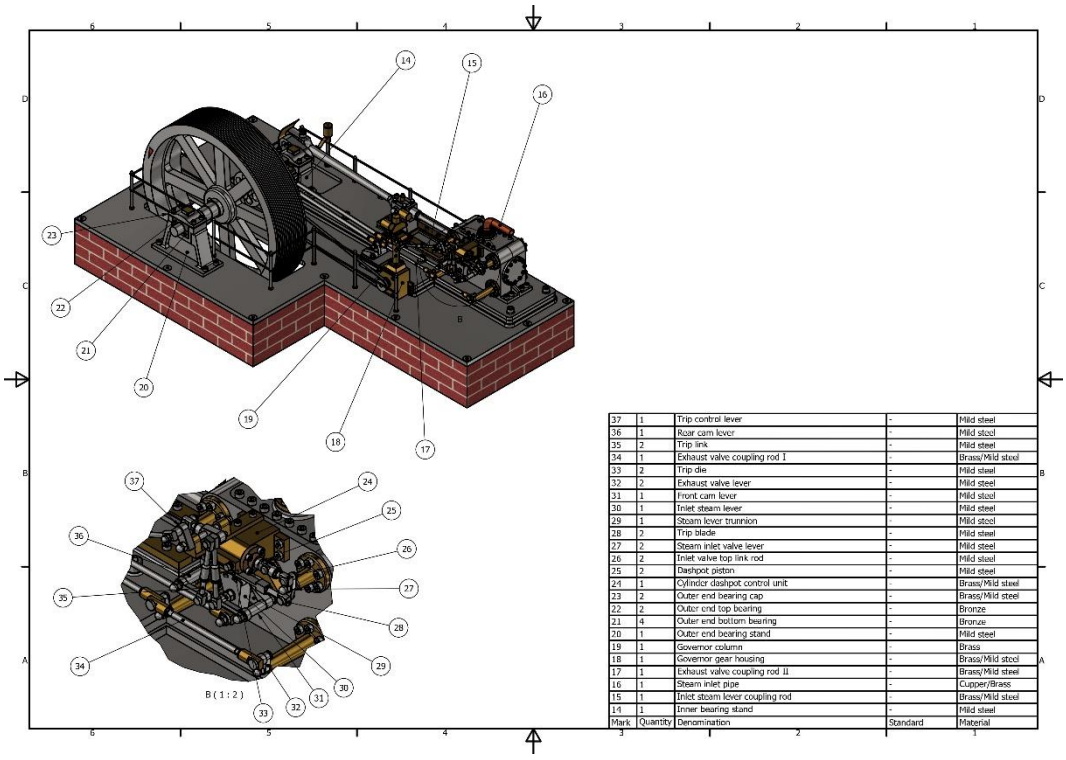
As previously mentioned, the assembly comprises 120 distinct elements, including demountable joining components such as headless screws, cap screws, dome nuts and washers, among others. However, to provide an accurate representation of the invention and facilitate the readability and comprehension of the assembly process, only four assembly drawings of the final assembly are presented (figures 2 to 5). These drawings exclusively feature the most notable and/or functionally significant elements of the invention, omitting the aforementioned demountable joining components. In each of these figures, different perspectives are shown that identify each of the elements that make up the historical invention. Likewise, each drawing details information about the element (mark), the number of identical components present in the assembly (quantity), its denomination (denomination), the applicable standard (standard) for standardized parts, as well as the material assigned to each component.

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Mark	Quantity	Denomination	Standard	Material
13	1	Crosshead	-	Bronze/Mild steel
12	2	Crosshead head guide	-	Brass
11	2	Crosshead side guide	-	Brass
10	2	Single arm valve rocker	-	Mild steel
9	1	Flywheel	-	Mild steel
8	1	Drive belt	-	Rubber
7	1	Cylinder block	-	Mild steel
6	1	Piston	-	Stainless steel/ Rubber
5	1	Connecting rod	-	Bronze/Mild steel
4	1	Engine bed plate	-	Mild steel
3	1	Crankshaft	-	Stainless steel
2	1	Crankshaft pulley	-	Mild steel
1	1	Brick base	-	Brick/Mild steel

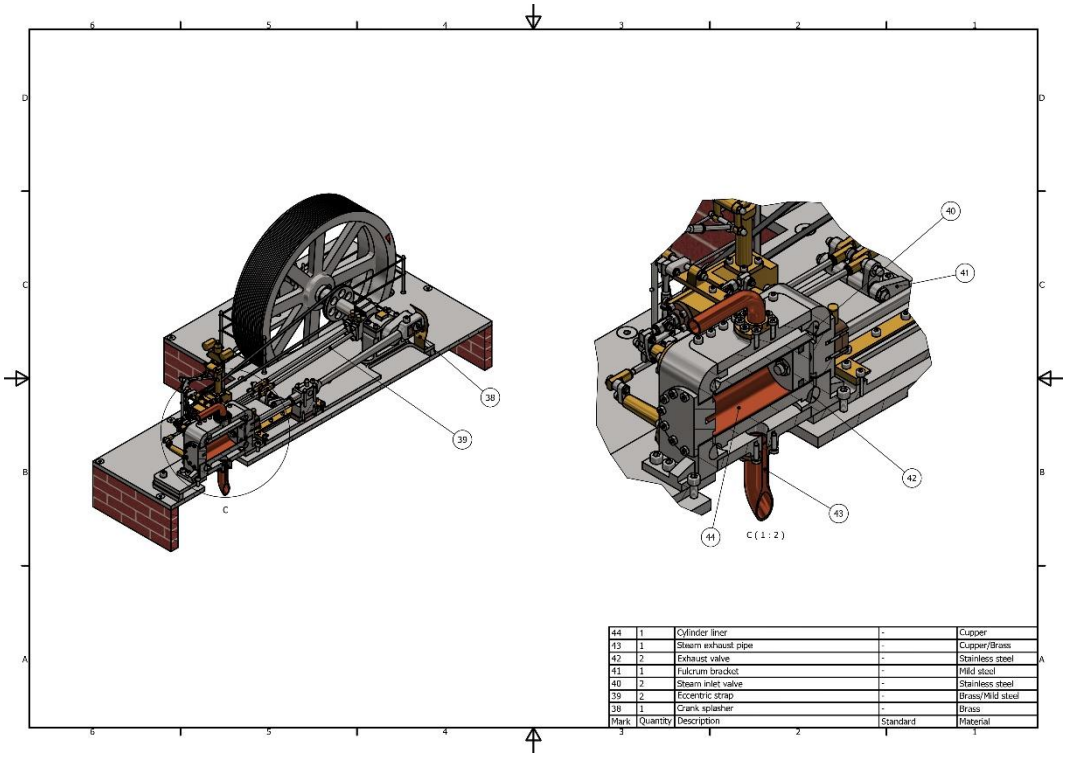
Fig. 2. Assembly plan (elements 1-13)



Mark	Quantity	Denomination	Standard	Material
37	1	Trip control lever	-	Mild steel
36	1	Rear cam lever	-	Mild steel
35	2	Trip link	-	Mild steel
34	1	Exhaust valve coupling rod I	-	Brass/Mild steel
33	2	Trip die	-	Mild steel
32	2	Exhaust valve lever	-	Mild steel
31	1	Front cam lever	-	Mild steel
30	1	Inlet steam lever	-	Mild steel
29	1	Steam lever trunnion	-	Mild steel
28	2	Trip blade	-	Mild steel
27	2	Steam inlet valve lever	-	Mild steel
26	2	Inlet valve top link rod	-	Mild steel
25	2	Dashpot pistón	-	Mild steel
24	1	Cylinder dashpot control unit		Brass/Mild steel
23	2	Outer end bearing cap	-	Brass/Mild steel
22	2	Outer end top bearing	-	Bronze
21	4	Outer end bottom bearing	-	Bronze
20	1	Outer end bearing stand	-	Mild steel
19	1	Governor column	-	Brass
18	1	Governor gear housing	-	Brass/Mild steel
17	1	Exhaust valve coupling rod II	-	Brass/Mild steel
16	1	Steam inlet pipe	-	Cupper/Brass
15	1	Inlet steam lever coupling rod	-	Brass/Mild steel
14	1	Inner bearing stand	-	Mild steel

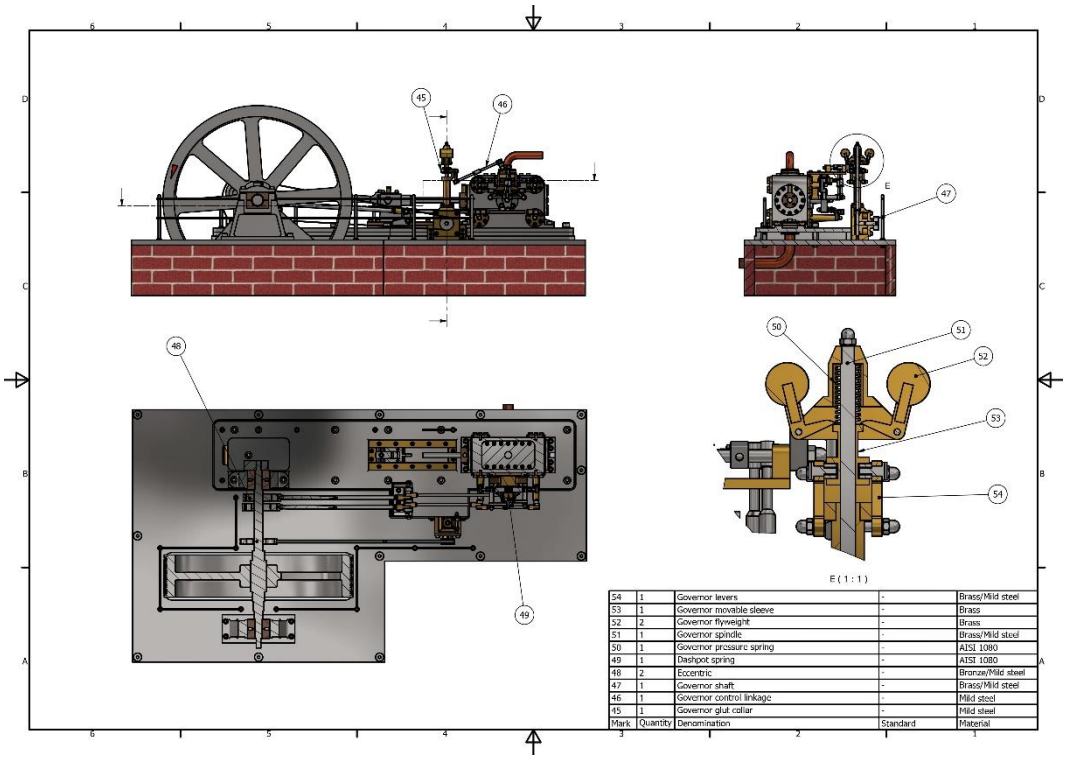
Fig. 3. Assembly plan (elements 14-37)

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Mark	Quantity	Description	Standard	Material
44	1	Cylinder liner	-	Cupper
43	1	Steam exhaust pipe	-	Cupper/Brass
42	2	Exhaust valve	-	Stainless steel
41	1	Fulcrum bracket	-	Mild steel
40	2	Steam inlet valve	-	Stainless steel
39	2	Eccentric strap	-	Brass/Mild steel
38	1	Crank splasher	-	Brass

Fig. 4. Assembly plan (elements 38-44)



Mark	Quantity	Denomination	Standard	Material
54	1	Governor levers	-	Brass/Mild steel
53	1	Governor movable sleeve	-	Brass
52	2	Governor flyweight	-	Brass
51	1	Governor spindle	-	Brass/Mild steel
50	1	Governor pressure spring	-	AISI 1080
49	1	Dashpot spring	-	AISI 1080
48	2	Eccentric	-	Bronze/Mild steel
47	1	Governor shaft	-	Brass/Mild steel
46	1	Governor control linkage	-	Mild steel
45	1	Governor glut collar	-	Mild steel

Fig. 5. Assembly plan (elements 45-54)

The three stages of the assembly process of this invention will be described in detail below, taking the previously mentioned

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

assembly plans as a reference. Furthermore, since the steam engine assembly was created from sub-assemblies, this process has been divided into several stages.

In the first stage, the fixed components of the historical invention are associated by means of multiple sub-assemblies, such as the base (brick base), crankshaft supports and engine bed plate, the cylinder block, and the governor gear housing.

The steam engine is supported by the brick base (1), which consists of a red clay brick foundation and a platform onto which the other components of the invention are inserted. The engine bed plate (4) is attached to this platform. The following components are secured to the engine bed plate:

- The crank splasher (38), which acts as a safety feature to protect users from the rotation of the crankshaft and its connection to the connecting rod (5).
- The crosshead side guides (11) and the crosshead head guides (12), which prevent the crosshead (13) from moving freely when the invention is in operation.
- Finally, the fulcrum bracket (41), which enables movement between the intake and exhaust coupling-rods.

Similarly, the cylinder block (7) is bolted to the engine bed plate. This is where the steam exchange occurs, making the steam engine's operation possible. As this is the first stage of assembly, focused on the fixed elements, the cylinder liner (44) is placed inside the cylinder block. The steam inlet pipe (16), the steam exhaust pipe (43), and covers are then added to close the openings for the piston and valves. This prevents steam loss and restricts the movement of the components, ensuring optimal operation. Additionally, the cylinder dashpot control unit (24) is affixed to the side of the cylinder block. This unit will later house the linkage system that allows the inlet steam levers (30) to be synchronized.

The bearings, which consist of an outer end top bearing (22) and two outer end bottom bearings (21), are installed in the inner bearing stand (14) and outer end bearing stand (20), respectively. These stands are secured to the brick base with cap screws. The outer end bearing cap (23) and a top lid are then attached, covering the space for bearing lubrication. This, along with the support provided, allows the crankshaft to operate optimally.

Finally, lubricators are inserted to provide lubricant to the constantly moving contact points. The governor gear housing (18), along with the associated governor column (19) and decorative elements like the handrails, are placed on the brick base.

Figure 6 shows the result of this first stage of assembly, which comprises most of the fixed elements of the invention.

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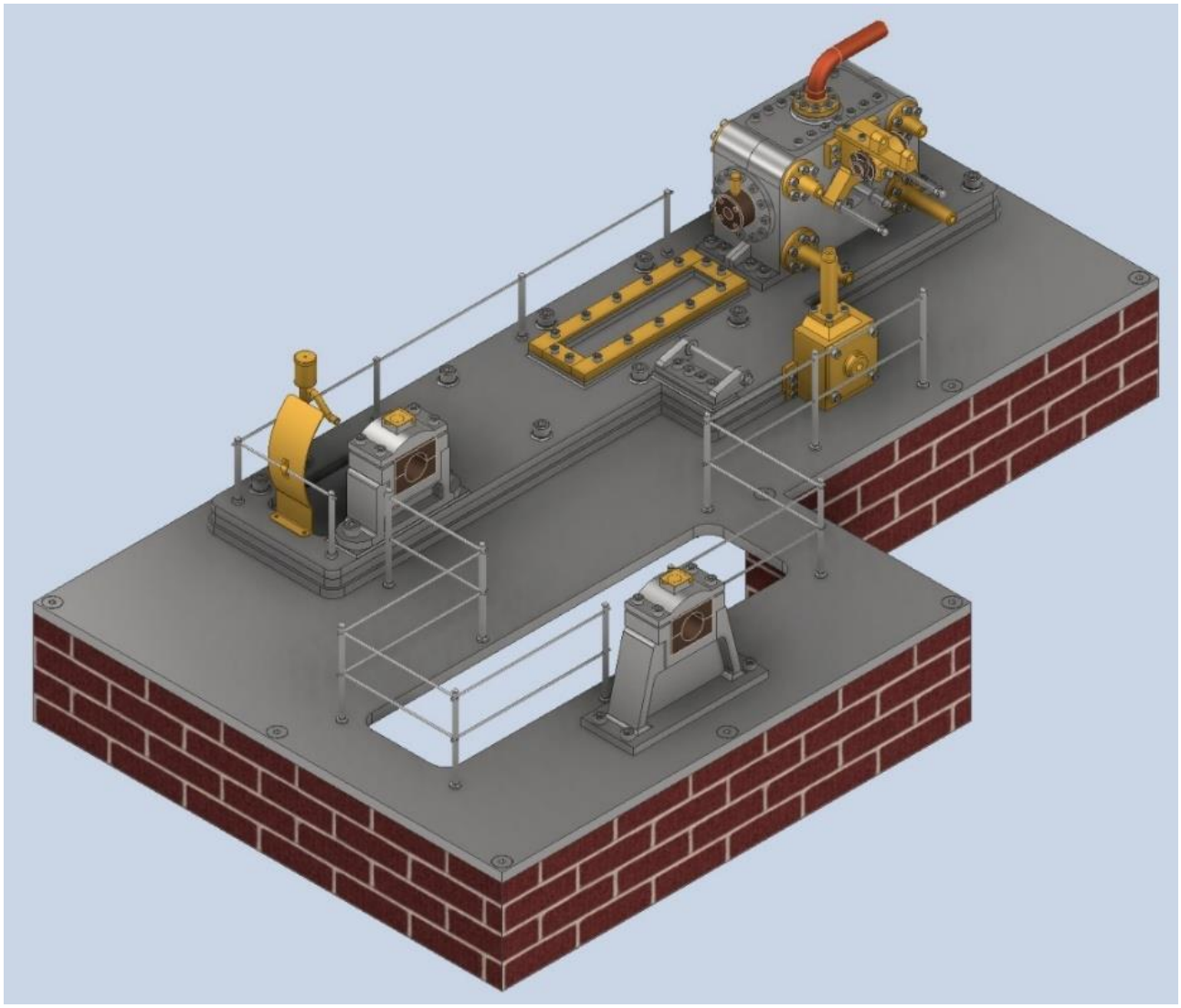


Fig. 6. Axonometric view of the first stage of the assembly

In a second stage, the mobile components responsible for the transmission of motion are incorporated onto the fixed elements arranged in the first stage.

Beginning with the cylinder block, the primary mobile component housed within is the piston (6), which executes a reciprocating linear motion. The piston is composed of a piston head and a piston rod joined together. Its movement, induced by the double-acting steam entering the cylinder block, is transmitted to the slipper crosshead. The crosshead is guided by the crosshead side guide and the crosshead head guide. It is connected to the piston via a threaded coupling on one end, while the other end is attached to the connecting rod. The function of the connecting rod is to convert this linear motion into rotational motion, which is then transmitted to the crankshaft (3). Grease fittings are located at the ends of the connecting rod to lubricate its connections with the crosshead and the crankshaft.

The crankshaft, supported by the inner bearing stand and the outer end bearing stand, incorporates a flywheel (9). The flywheel's purpose is to create rotational inertia, ensuring the invention operates as smoothly and efficiently as possible. The crankshaft also features a cavity for attaching the crankshaft pulley (2), which transmits rotational movement to the governor shaft (47) via the drive belt (8).

The governor plays a crucial role in regulating the engine's speed and, consequently, controlling the steam flow to ensure optimal performance. Movement from the governor shaft is transmitted to the spindle (51) by two internal bevel gears. Housed within the spindle are two flyweights (52), one on each side. When the spindle rotates, these flyweights create rotational inertia, and their

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

position varies with the speed. They move to an open position to increase speed or a closed position to decrease it. This action, transmitted through the front and rear cam levers (31) and (36), automatically controls the steam engine's operating velocity. Additionally, a pressure spring (50) is located inside, compressed by the movable sleeve (53). The vertical position of this sleeve directly affects the steam inlet and exhaust through its interaction with the cams.

Figure 7 shows the result of this second stage of assembly which, together with the fixed components, comprises all the moving elements that work in the transmission of movement.

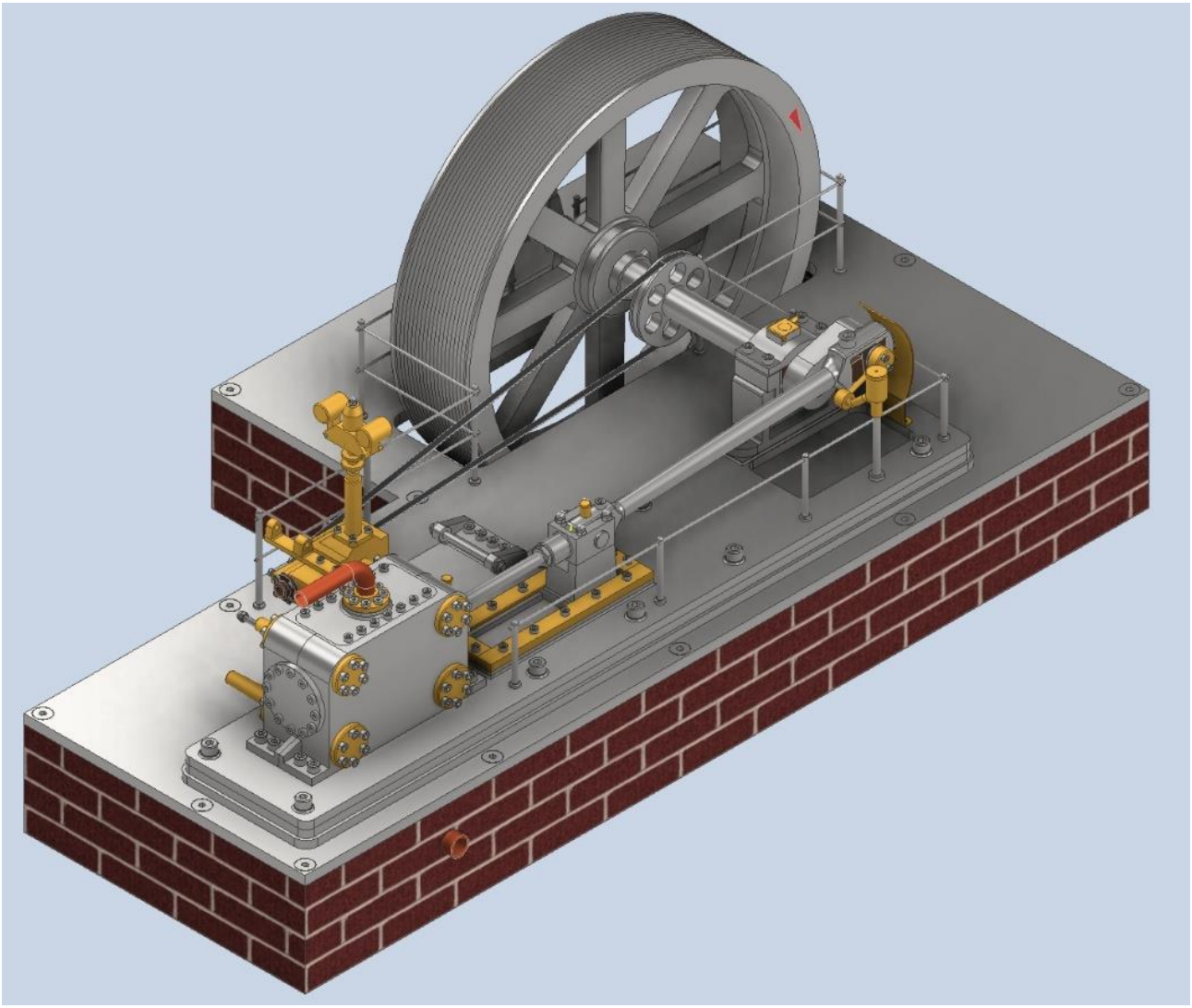


Fig. 7. Axonometric view of the second stage of the assembly

Finally, in the third and final stage of assembly, the linkage system that actuates the intake and exhaust valves is inserted, thus creating the Corliss valve gear present in this historical invention.

The valves located within the cylinder block are actuated by two eccentrics (48) on the crankshaft, positioned 20º apart to optimize steam flow between intake and exhaust. These eccentrics are housed within an eccentric strap (39), which includes an oiler on top.

The eccentric positioned furthest from the flywheel directly transmits motion to the inlet steam lever, which contains a trip die (33) for each of its toothed spaces. The lever is housed in the steam lever trunnion (28) and connected via an inlet steam lever coupling rod (15) secured by a dome nut. The connection between the eccentric strap and the coupling rod is made at the single arm valve rocker (10), which is attached to a fulcrum bracket to limit its oscillation.

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

The operation of the steam inlet valves (40), located on the upper part of the cylinder block, is initiated by the oscillating motion of the inlet steam lever. This movement is transmitted to a trip blade (29), which in turn is connected to the steam inlet valve lever (27) for each valve. Each lever has two cavities: one at the bottom for connection with the trip blade, and another for the inlet valve top link rod (26), which is topped by a nut and connected to the dashpot piston (25). The dashpot spring (49) is located in the space between the two pistons, all within the control unit. This arrangement synchronizes the relative movement of the two intake valves. To prevent them from dislodging and to ensure optimal function, a cover is attached on both sides of the control unit.

In parallel, the eccentric strap is joined to an exhaust valve coupling rod II (17) by a rocker arm bolt, which is located in a second single arm valve rocker attached to the fulcrum bracket. This longer exhaust valve coupling rod II is linked to another exhaust valve coupling rod I (34). These rods are connected to the first exhaust valve (42) via the exhaust valve lever (32) using a mechanical fastener. A similar spacer and bolt at the opposite end link the movement to the lever of the second exhaust valve. This synchronization of the exhaust valves, along with the two inlet valves, generates a double-acting steam flow inside the cylinder.

As previously described, the rotational speed of the governor varies the vertical position of the movable sleeve. Through the connection of the glut collar (45), which is fixed to the movable sleeve by the cam levers and the governor lever (54), the position of the rear cam lever and front cam lever is determined. This directly affects the opening and closing of the inlet valves, and consequently, the engine's speed.

An increase in the operational speed of the engine causes the governor flyweights to move outward, increasing inertia and raising the movable sleeve. This action modifies the position of the trip links (35), causing both the rear and front cam levers to incline upward from their initial position. This inclination obstructs the passage of the trip blades, thereby reducing the speed of the steam engine.

This system includes the governor control linkage (46), which is directly connected to the aforementioned front and rear cam levers and the governor lever at one end. At the other end, it connects to the trip control lever (37), which is affixed by nuts to a component of the cylinder dashpot control unit. The two-trip links, connected from the trip control lever, join the rear cam lever and the front cam lever. The position of these cam levers guides the two trip blades, enabling the regulation of valve actuation speed and creating a feedback system.

Finally, figure 8 shows the linkage system that actuates the intake and exhaust valves of the Corliss valve gear, which controls the amount of steam input.

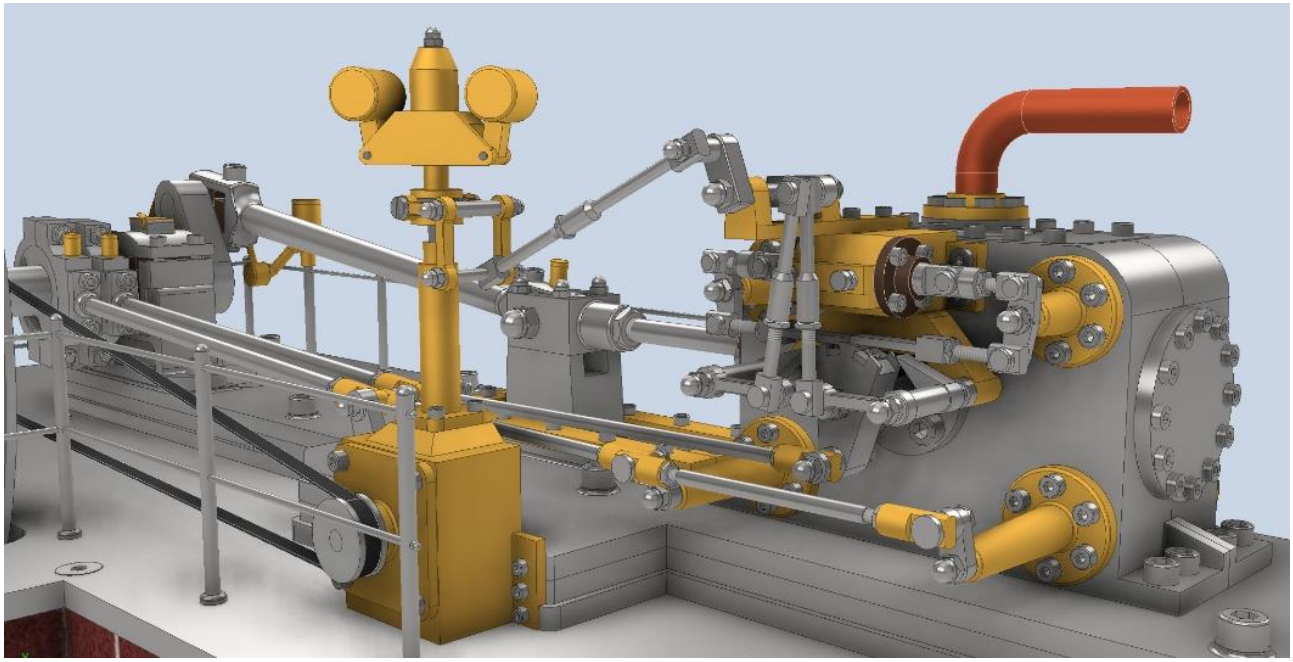


Fig. 8. Three-point perspective of the third stage of the assembly

Likewise, a 158 MB virtual recreation final video, with a duration of 1 minute and 11 seconds, has been generated in .mp4 format utilizing the Inventor Studio module within Autodesk Inventor Professional 2024. This final video comprises three distinct videos with

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.XX nºX DOI: https://doi.org/10.6036/XXXX

seamless transitions. The first video presents a rotational sweep, commencing from the flywheel and concluding with a comprehensive view of the historical invention in operation. Subsequently, the second video features a longitudinal camera traverse, extending from the crankshaft to the actuation of the Corliss valves, with transparency applied to the cylinder block and the governor gear housing. The third video focuses on demonstrating the piston's operation within the cylinder block through a sectional view, also highlighting the movement of the crosshead and its associated assemblies.

4. - CONCLUSIONS

This paper presents the steps followed in the assembly process of a historical invention designed by Arnold Throp and published in the «Model Engineer» magazine in 1982, based on the reproduction of its plans made by Julius de Waal in 2018. It is a single-cylinder high-pressure steam engine with a Corliss valve gear. For this purpose, the design software Autodesk Inventor Professional 2024 was used, which allowed us to obtain reliable graphic documentation in the form of assembly and subassembly drawings, detailed perspectives, as well as detail drawings of the different elements and exploded perspectives. Likewise, and thanks to the Inventor Studio module incorporated in the aforementioned software, it was possible to obtain a virtual recreation that shows the operation of this invention, highlighting the linkage system that actuates the intake and exhaust valves, and that constitute the Corliss valve gear system.

However, in the three-dimensional modeling process, there were some drawbacks derived from the lack of knowledge of some dimensions in some elements, which were resolved by knowing the location of these components in the assembly or had to be resized, due to geometric interferences in the assembly process, so that this assembly was coherent and functional. Likewise, there have been other drawbacks such as that the software does not consider the deformation of components made with elastomeric materials such as the drive belt.

Likewise, certain degrees of freedom of each element, which are influenced by the type of constraint (geometric, dimensional and movement), have not been allowed, obtaining a coherent and functional 3D CAD model, which has an appropriate relative movement between elements, applying an interference analysis.

On the other hand, the process of recreating historical machines—using digital technologies—could be used as a valuable teaching-learning method in university teaching, where different disciplines could be worked on transversally. A digital 3D model of an industrial-era engine serves both engineering education and museum contexts. Therefore, application potential is high, especially if supported by practical classroom testing. To strengthen the applied value of this research, the first step involves presenting a virtual recreation that illustrates the invention's functionality. Subsequently, a 3D-printed physical model of the invention could be produced to facilitate a comprehensive understanding of the function of each of its constituent elements. Therefore, it can be concluded that engineering graphics serves as an effective tool for the valorization and promotion of industrial heritage.

Finally, and as possible work, a linear static analysis of the invention could be carried out under real operating conditions by the finite element method. In this way, a numerical simulation of the 3D CAD model could be carried out, to know if the invention was oversized or not, according to material strength criteria, analyzing possible optimizations on the design of the aforementioned invention.

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