

Simulation and Modeling of a Reciprocating Plunger Steam Engine to Obtain Two Indicator Diagrams

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Abstract: Located at the National University in Bogotá, Colombia, this paper presents the development of the integration of kinematics, simplified kinetic and zero-dimensional models of indicator diagram of a double-acting, single-cylinder steam engine; the model integration is done for two configurations of the distribution system to simulate the instantaneous torque and the average. Two simulations are carried out at different steam entry conditions and an advance angle of 0° for the distribution system, fed with the data obtained from the characterization and metrological survey of the VE (vapor engine) parts in a CAD (computer-aided design) system. It is verified that integrating the models constitutes a simulation tool that allows for the instantaneous torque deliveries and average torque of the accurate operation's VE.

Key words: Kinematics, kinetics, indicator diagram, live steam, expanding steam.

1. Introduction

This studied mechanism is an engine with a double effect cylinder. It is fed from a boiler to generate heat, thus increasing the temperature and pressure of the water to obtain vapor at an average of 96 psi. The engine is provided with a plunger with alternative motion, a horizontal provision in double effect (two strokes of work for every turn of 360 degrees of the flywheel). This development of the study is without condensation at the exit of the engine. Following Fig. 1 shows the superior view of the VE (vapor engine); in this image are the essential parts, the inside effect is located on the left side of the piston; meanwhile, the exterior effect is located on the right side.

The valve's position and the motion of the reel define the entry or the vapor exit. The vapor entries in high pressure and temperature when the piston is in the TDC (top dead center), the vapor pressure pushes

the plunger to the other side, precisely the BDC (bottom dead center). The thermal energy is converted in this mode in mechanical energy. The piston has an alternative movement than after the vapor entries for another orifice, helped by the valve type slide's movement, generating the piston's work repeating the action in a wrong way. The piston's horizontal movement in sway mode is converted later into rotatory motion thanks to the set connecting rod-crank, giving out the rotation to the flywheel [1].

2. Construction of Indicator Diagram

An indicator diagram is built starting from the obtained information of pressure and volume in all the points displaced by the piston. The data are analyzed in every instant that makes up a process due to the properties' changes. For the indicator diagram's construction, it is necessary to set the VE distribution system's configuration, determining the time duration in every process. Next is described the process that makes up the indicator diagram in the arrangements for live vapor and vapor in the expansion coefficient [1].

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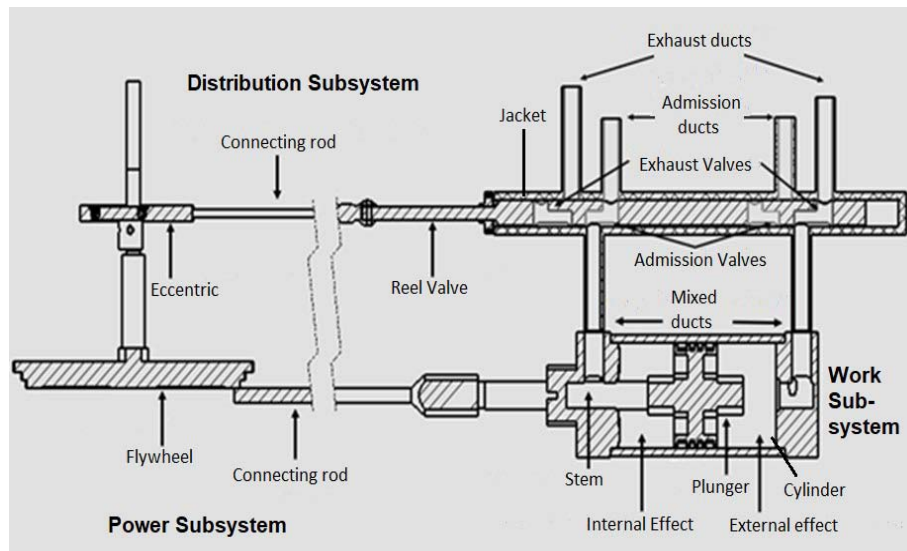


Fig. 1 VE parts in double effect configuration.

2.1 Indicator Diagram: Live Vapor

Fig. 2 shows the indicator diagram developed and shows intake and exhaust processes in a valve with constant vapor entries, where the pressure is equal to the intake pressure. Theoretically, this is equal to the boiler pressure due to losses not being contemplated. Then below is the description of every process in the diagram [2].

Intake: A-B isobaric process (constant pressure)

Exhaust: B-C isochoric process (constant volume)

Exhaust: C-D isobaric process (constant pressure)

Intake: D-A isobaric process (constant volume)

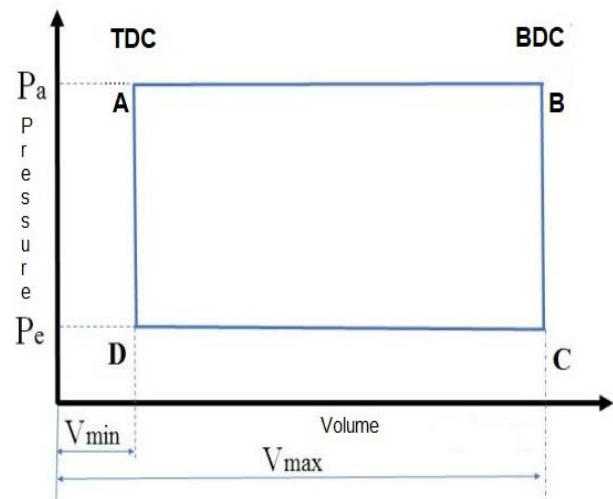


Fig. 2 Live vapor reel, theoretical P - V diagram.

2.2 Indicator Diagram: Expansion Vapor

Fig. 3 shows the VE indicator diagram that works with a configuration in the distribution system with intake cut (expansion). Below is the description of the processes that compose the operating cycle [3].

Intake: F-A isochoric process (constant volume)

Intake: A-B isobaric process (constant pressure)

Expansion: B-C adiabatic process (without heat interchange)

Exhaust: C-D isochoric process (constant volume)

Exhaust: D-E isobaric process (constant pressure)

Compression: E-F adiabatic process (without heat interchange)

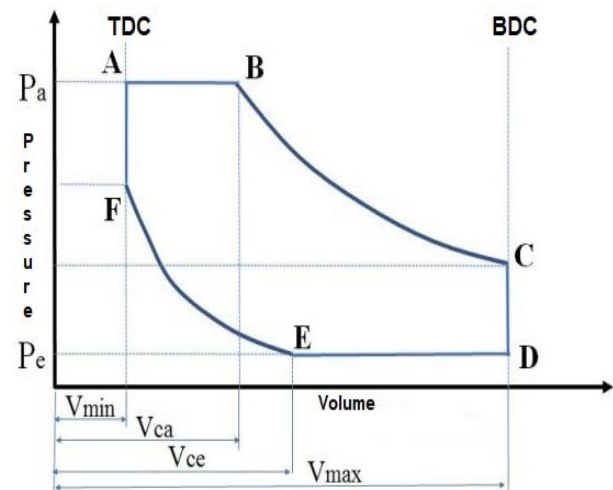


Fig. 3 Expansion vapor reel, theoretical P - V diagram.

3. Simplified Kinematic and Kinetics

This principle of mechanism’s kinematic analysis is employed to develop equations to calculate positions, velocities, and accelerations; this is based on the simple geometry of the set connecting rod-crank, shown in Fig. 4, which used equations in the function of turn angle in the crank.

The formed triangles are shown in Fig. 4, using the trigonometric relationship and the binomial expansion, are obtained by Eq. (1), representing the piston’s approximate position [4].

$$x \cong l - \left(\frac{r^2}{4l}\right) + r \left(\cos wt + \frac{r}{4l} \cos 2wt\right) \quad (1)$$

Deriving Eq. (1) is obtained; Eqs. (2) and (3) represent the piston velocity and the acceleration, respectively.

$$\dot{x} \cong -rw \left(\sin wt + \frac{r}{2l} \sin 2wt\right) \quad (2)$$

$$\ddot{x} \cong -rw^2 \left(\cos wt + \frac{r}{l} \cos 2wt\right) \quad (3)$$

For the simplified kinematic analysis, equations are employed to determine the vapor torque Eq. (4), the inertial torque Eq. (5), and the total torque Eq. (6) [2].

$$T_{v21} = F_g r \sin wt \left(1 + \frac{r}{l} \cos wt\right) \quad (4)$$

$$T_{i21} = \frac{1}{2} m_B r^2 w^2 \left(\frac{r}{2l} \sin wt - \sin 2wt - \frac{3r}{2l} \sin 3wt\right) \hat{k} \quad (5)$$

$$T_T = T_{i21} + T_{g21} \quad (6)$$

3.1 Methodology

They are employing the kinematic and kinetic equations proposed in the book of design of machinery of Robert Norton, where the analysis in a single-cylinder engine is realized, making the necessary adjustments to adequate the equations in the prototype VE in double effect. The indicator diagram is integrated into a 0-dimensional model to obtain the instantaneous torque and medium torque. Also the analysis for two configurations is realized in the distribution system: live vapor and expansion vapor.

It effectuated the construction of the 3D layouts with the VE metrological assurance for every configuration of the distribution system using the design software Solid Works, which allows obtaining the engine’s design parameters to realize the integrated simulation. This process is realized with the following steps:

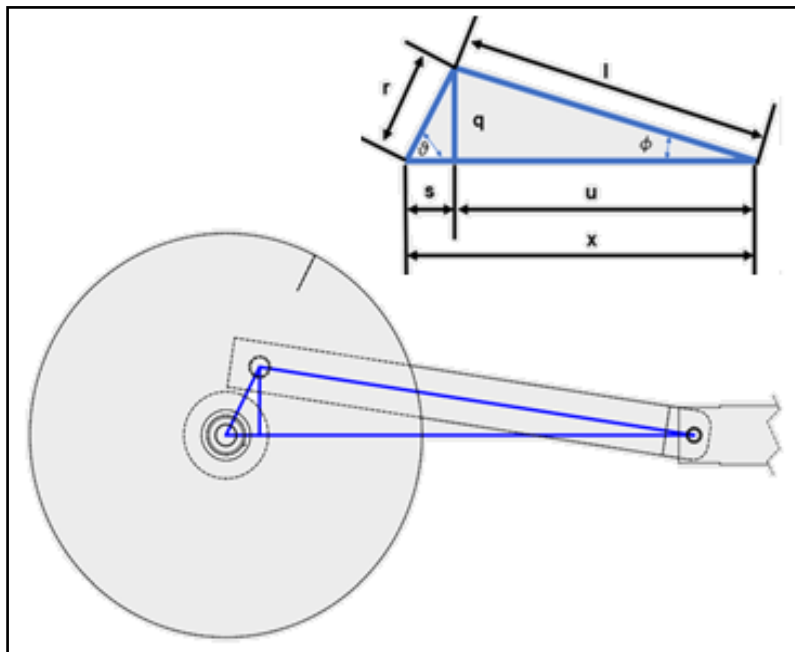


Fig. 4 Geometry of the mechanism, connecting rod, and crank.

- (1) Recognizing and characteristics.
- (2) Metrology.
- (3) Build-in CAD (computer-aided design).
- (4) Assembly of parts.
- (5) Comparison with an actual prototype.
- (6) Improvements.

Moreover, of the obtained design parameters in the 3D plans, the model is fed to entry parameters obtained from experimental tests and calculated parameters. The integration of the kinematic, simplified kinematic, and indicator diagram model is realized in 4 steps explained in Sections 3.2 and 3.3.

3.2 Develop Simplified Kinematic and Kinetic Verification

With the engine software's uses from Norton's book, the model's comparison was found different in acceleration and inertial torque because they approximated the proposed equations. They use only the first two terms in the radical obtained from the binomial expansion.

To obtain a comparable value from the software Engine, the proposed model includes the third term in the binomial expansion receiving the equations from a position, velocity, piston acceleration, and inertial torque how as shown below.

Position

$$x = l - \left(\frac{r^2}{4l}\right) - \left(\frac{r^4}{32l^3}\right) + r \left(\cos wt + \frac{r}{4l} \cos 2wt + \left(\frac{r^3}{16l^3}\right) (\cos 2wt) - \left(\frac{r^3}{32l^3}\right) (\cos^2 2wt) \right) \quad (7)$$

Velocity

$$\dot{x} = -rw \left(\sin wt + \frac{r}{2l} \sin 2wt + \frac{r^3}{8l^3} \sin 2wt - \frac{r^3}{16l^3} \sin 4wt \right) \quad (8)$$

Acceleration

$$\ddot{x} = -rw^2 \left(\cos wt + \frac{r}{l} \cos 2wt + \frac{r^3}{4l^3} \cos 2wt - \frac{r^3}{4l^3} \cos 4wt \right) \quad (9)$$

Inertial Torque

$$Ti = mB \left(-rw^2 \left(\cos wt + \frac{r}{l} \cos 2wt + \frac{r^3}{4l^3} \cos 2wt - \frac{r^3}{4l^3} \cos 4wt \right) \right) \left(\frac{r}{l} \sin wt \left(1 + \frac{r^2}{2l^2} \sin^2 wt + \frac{3r^4}{8l^4} \sin^4 wt \right) \right) \left(l - \left(\frac{r^2}{4l} \right) - \left(\frac{r^4}{32l^3} \right) + r \left(\cos wt + \frac{r}{4l} \cos 2wt + \left(\frac{r^3}{16l^3} \right) (\cos 2wt) - \left(\frac{r^3}{32l^3} \right) (\cos^2 2wt) \right) \right) \quad (10)$$

The engine software predetermines the exercised force on the top face of the piston to check the model. Two checks were made for the kinematic model, one for the power subsystem and the other for the distribution subsystem, doing the respective check for the simplified kinematic model from the power subsystem.

3.3 Zero Dimensional Integration of Kinematic and Kinetic Models in Live Vapor Whit Simple Effect

Zero dimensional indicator diagram model.

Volume: Determining the work inside the cylinder and correlating it with every crankshaft turn grade is used in the CAD model. Initially, the piston is drawn and put in TDC, making a geometrical picture of the compression camera. The software to build this is Solid Works to calculate the volume (dead volume external effect) $V(me)$. Converting this data into an entrance parameter for the model, also can calculate the volume in function of the piston movement by multiplying the piston area (Ap), for the position of the same ($x(PMS)$) to this product is summed the dead volume how is shown in Eq. (11).

$$V(x(ref)) = (x(pms))(Ap) + (Vem) \quad (11)$$

Pressure: It is necessary to determine the instant where the exhaust and intake valves are opened. To integrate the pressures in the intake and exhaust with the crank's turn angle, the kinematic model of the distribution subsystem is used that permits calculation of their position. The start position in the distribution subsystem with the power subsystem's function is showed in Fig. 5.

Figs. 5 and 6 show the reel part of the distribution subsystem's configuration. A point of reference marked with 0 measured the reel's distance to the

extreme points in the entry and exit duct in the distribution jacket. Fig. 5 shows the intense moments of the valves. Fig. 6 measures the valves' distances and equalizes the crank angle to 0° [5].

Next is established the following conditions: if the intake valve is opened, the mathematic model adds the intake pressure, and if the exhaust valve is opened, the model adds the exhaust pressure. It is necessary to determine the gap angle between these two subsystems to correspond the pressure values to the piston position—finally, the position in the distribution subsystem with the power subsystem's function in Fig. 7.

This integration includes the found pressure in the zero dimensional model, which is a function of volume. It depends on this position, making a relationship in the acting strength on the piston face with the connecting rod's turn angle. This strength is calculated in the next Eq. (12):

$$F(V) = \frac{\pi}{4} P(V) B^2 \quad (12)$$

where:

- B = Piston diameter
- $P(v)$ = Vapor pressure
- $F(v)$ = Vapor strength

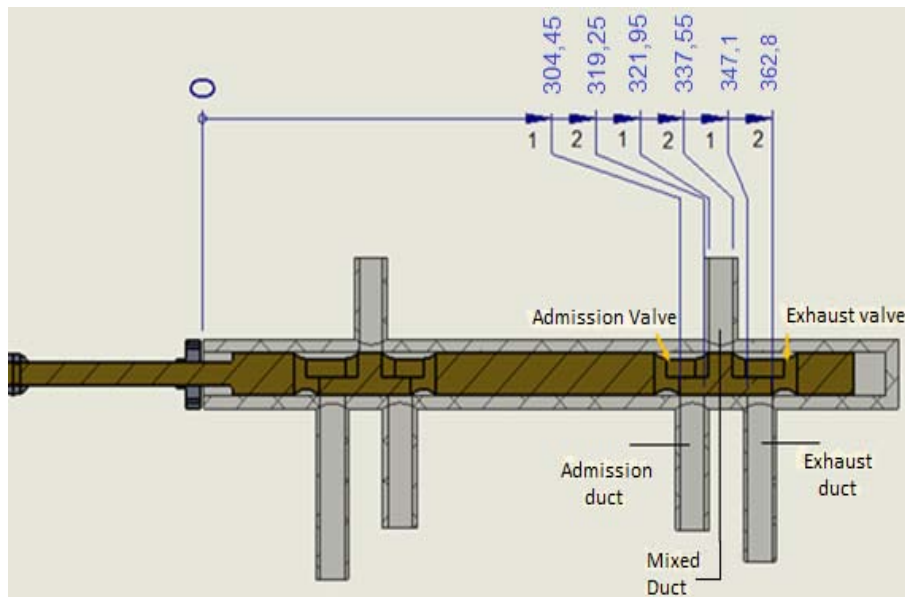


Fig. 5 Overlap position, distribution subsystem reel.

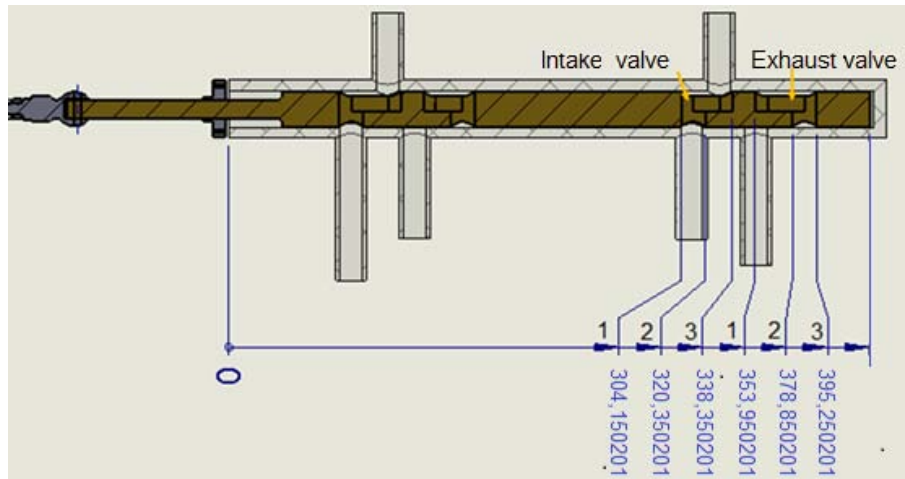


Fig. 6 Maximum point of admission in TDC, distribution subsystem reel with external effect.

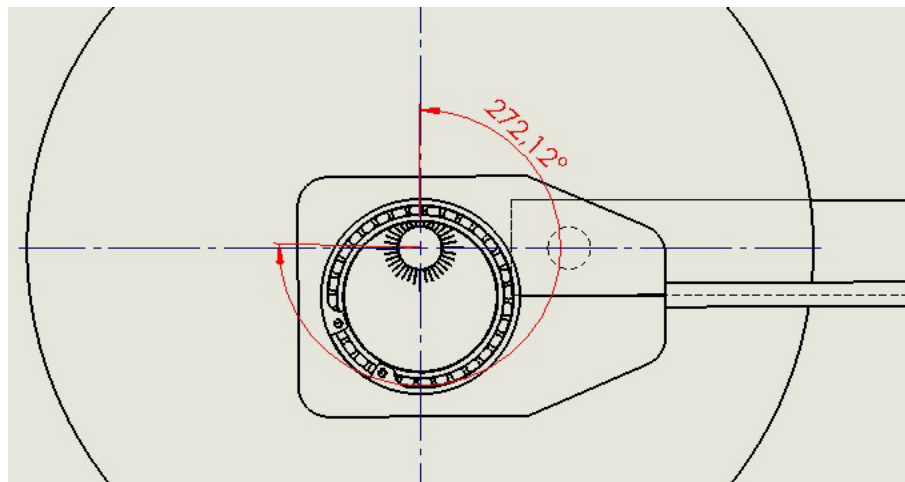


Fig. 7 Gap angle in TDC between the distribution and power subsystem.

The vapor strength can calculate the vapor torque and total torque; the medium torque T_m is the average in 720 obtained dates for the instantaneous full torque T_t shown in Eq. (13).

$$T(m) = \frac{(\sum_{n=0}^{720} T_{Tn})}{720} \quad (13)$$

3.4 Kinetic and Kinematic Integrations in Cero Dimensional Mathematical Models

An integrated built model for a simple effect engine in live vapor condition needs to aggregate the indicator diagram and the vapor torque generating the external effect. It contemplates the pressure losses in the intake and exhaust pipes.

The vapor torque for the external effect T_{ev} is calculated with Eq. (7), while the vapor torque in

internal effect T_{iv} is calculated with Eq. (14). Notice this expression rests the angular velocity product and when the crank is located at 180° ; this is due to the piston reaching TDC in internal effect for this condition.

$$T_v = F_v r s e n(wt - wt(180^\circ)) \left(1 + \frac{r}{l} \cos(wt - wt(180^\circ)) \right) \quad (14)$$

The vapor torque is the sum of the torques previously mentioned.

3.5 Kinetic and Kinematic Integrations in Cero Dimensional Mathematical Models in the Effect of Double Expansion

The integration of the cero dimensional model

with the simplified kinematic and kinetic model for a VE is realized with double effect with a configuration in the valvular distribution subsystem to cuts in the admission in 59.1%. The simplified model used in this integration is equal to that shown in Section 3.4. In the indicator, diagram the principal difference due to the admission cut before the BDC (closes in intake valve), generated a polytropic expansion. The exhaust valve locks before TDC develops a polytropic compression. Also, to establish the condition of openness and closes of the valves, it is necessary to determine the direction of the plunger's movement to identify the time of compression and expansion.

3.5.1 Expansion Time

The expansion time is generated after the admission of valve closes; this is characterized because the piston moves from TDC to BDC, with the valves staying closed. When these conditions are fulfilled, the model calculates the pressure inside the cylinder with Eq. (15).

$$p = \frac{c}{V^n} \quad (15)$$

In the polytropic Eq. (17), n is the exponential, and C is the constant of proportionality [6].

3.5.2 Compression Time

The compression time is generated after the exhaust valve's close; this is characterized because the piston moves from BDC to TDC, and the valves remain closed. At the beginning of the compression stroke, the mathematic model calculates the constant (c) in Eq. (15). It is known as a polytropic exponential (n), the constant (c), volume for each turn degree in crank; the pressure can be calculated at every point of the curve. When these conditions are accomplished, it needs to consider the quantity of remainder mass (mass inside the cylinder in the instant when the exhaust valve closes) to determine if the compression time follows the trajectory of Eq. (15) due to the polytropic compression or follows a different course.

4. Results

The following parts are shown in isometric form all the assembly of the VE with the Prony brake, an instrument to obtain torque and power. Too in the experimental proof processes, the indicator diagrams obtained in internal and external effect with use of reel valve with different configurations like live vapor and vapor in expansion coefficient [7].

4.1 Drawing Plans

Fig. 8 shows the assembly of the 3D drawing plans on the VE, also the subsystems of power (2), distribution (3), Prony brake (4), intake pipes (5), and exhaust (6) are shown.

4.2 Develop Indicator Diagrams

In live vapor conditions, the configuration is effectuated by two diagrams indicated in different vapor entry conditions. This first condition was with saturated steam and the live vapor reel; the second condition used overheated vapor and the reel of expansion vapor. These graphics are realized with 0 degrees of advance angle in the distribution subsystem when the piston in external effect is in TDC and the intake valve begins opening [8].

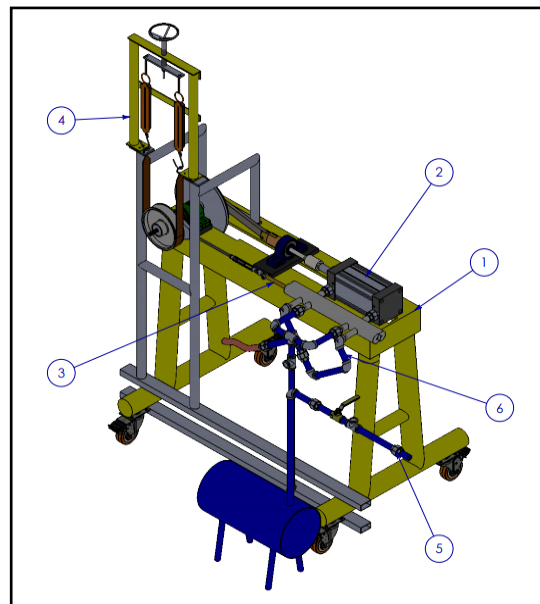


Fig. 8 3D assembly of VE.

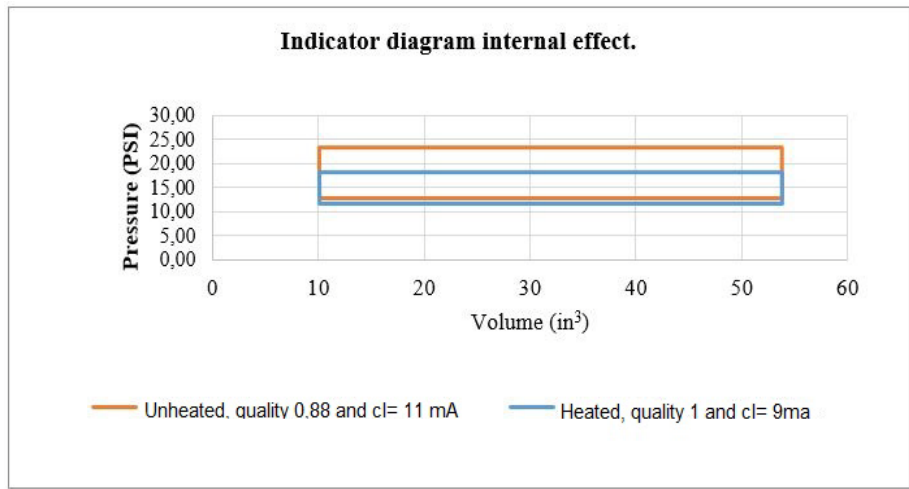


Fig. 9 Indicator diagram, with internal effect in live vapor configuration.

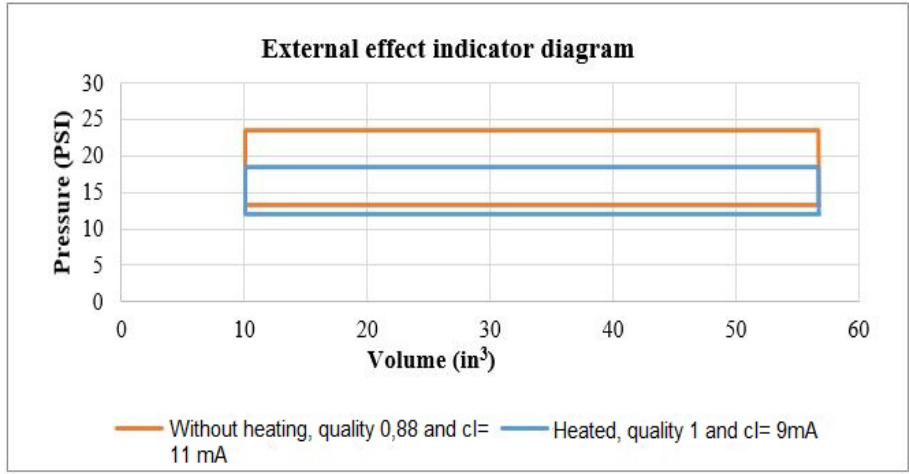


Fig. 10 Indicator diagram with external effect configuration using the live vapor reel.

Fig. 9 shows the indicator diagram of the internal effect for a live vapor configuration while Fig. 10 shows the same graph but with an external effect. After the operation conditions are achieved, the different indicated diagrams from the experimental stage are obtained with the VE with the entry parameters, and a practical design is proposed.

4.2.1 Expansion Reel Configuration

Figs. 11 and 12 show the indicator diagrams for the reel valve type’s internal and external effects, with design in expansion coefficients.

5. Simplified Kinematic Simulation

With the comparison in the results from the software engine, Fig. 13 shows the vapor’s behavior

in the generated torque, showing the inertial torque in Fig. 14 and torque total Fig. 15. This last represents the instantaneous torque for every crank turn grade.

Fig. 15 shows the total vapor torque for an expansion reel-type configuration. It presents similar maximums points for every effect, in difference with the full vapor torque in a live vapor configuration, which is evidence of higher torque in external effect than the internal.

The obtained dates of medium torque from the simulation and the experimental test are shown in Fig. 16 with trends of two curves, which checked the entered model is an approximated tool to calculate the medium torque delivered by the VE.

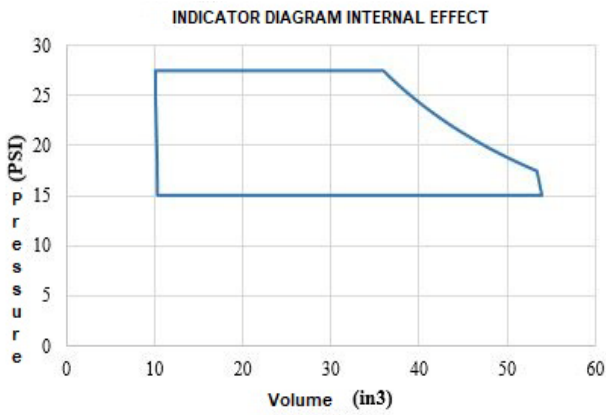


Fig. 11 Indicator diagram, internal effect in expansion reel configuration.

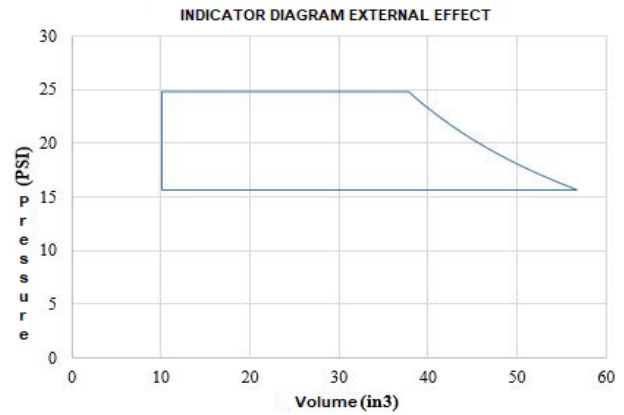


Fig. 12 Indicator diagram, external effect with a configuration in expansion reel.

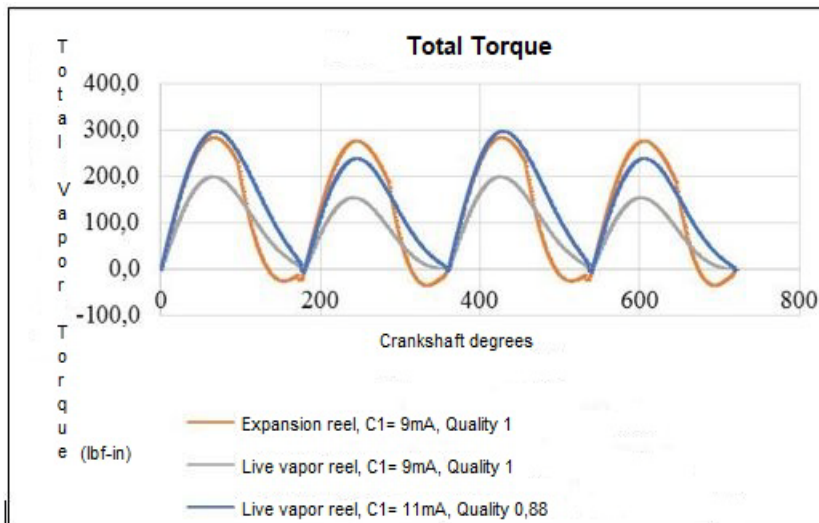


Fig. 13 Vapor total torque.

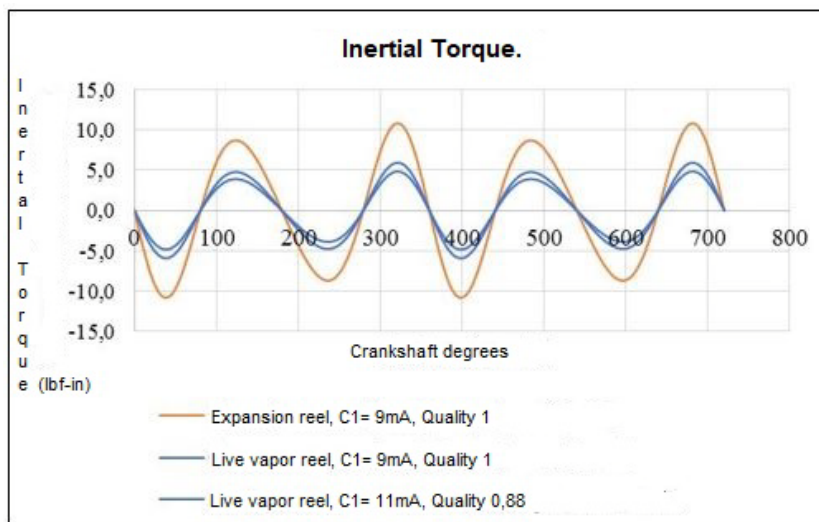


Fig. 14 Inertial torque.

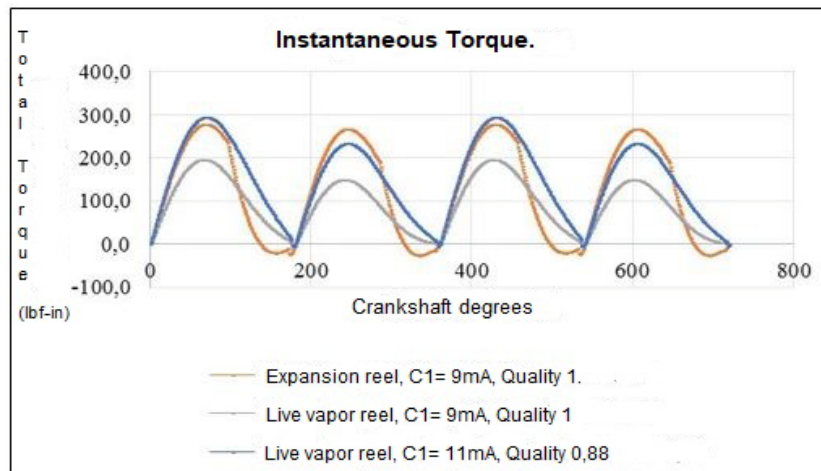


Fig. 15 Total torque (instantaneous).

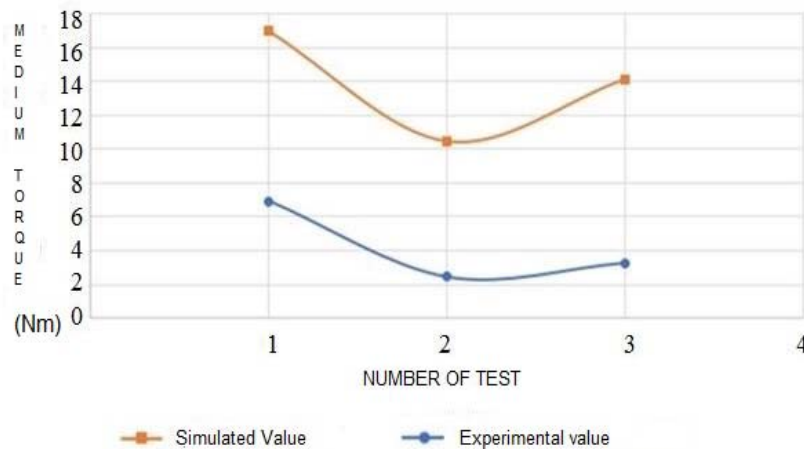


Fig. 16 Model check.

6. Conclusions

- The 3D modeling was a fundamental tool to fine-tuning the VE to obtain the experimental results, showing the exact positions of functioning from the visualization in the internal geometric relations between the reel valve, the jacket, and the set piston-plunger. All this is to associate the turn angle in the connecting rods in the distribution and power subsystems.
- The indicator diagram construction was necessary to know relative positions between the subsystems of distribution and power for every configuration; according to the kinematic model built, the volume inside the cylinder is the piston position’s function, depending directly on the connecting rod’s angle.

Finally, the gas’s pressure on the piston face depends on the open and close state in valves and the direction of piston movement.

- This work allowed the construction of the indicator diagrams in the VE for the configurations on coefficients of live vapor and expansion vapor, in a condition of cut admissions in 59.1% for external effect and 59.2% for internal effect, with an advance of 0°.
- This methodology shows the detailed form for the construction and simulation in other configurations in the distribution subsystem.
- The inertial torque generated by the steam engine is not an expected value for calculating the total torque in the functioning conditions of the engine due to this engine working at low revolutions growing up with more power.

- The steam engine's integrated simulation with a configuration in an expansion double effect reel-type shows the total torque representing similar maximum points for every effect, in difference with the full vapor torque for the live vapor configuration. There is a higher torque in the external effect than the internal effect, allowing a more homogeneous movement in the power subsystem and the experimental tests.

- This research has checked the models' integration, constituting a simulation tool that enables approximate results of instantaneous torque and medium torque in the VE regarding the accurate operation.

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