MATEC Web of Conferences **108**, 04001 (2017) DOI: 10.1051/matecconf/201710804001
ICMAA 2017

Study of Different Factors Influence on Thermocompressor Performance

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Abstract. This article deals with investigation of different factors influence on thermocompressor. These factors include regeneration efficiency, dead volume, working frequency, heat transfer coefficient, thermocompressor diameter and fins application. Calculation shows that most influential factors are regeneration efficiency, dead volume and diameter. It was also found that fins application is not effective for thermocompressor performance enhancement.

1 Introduction

Thermocompressor (TC) is a device which transform heat directly to a potential energy of pressure. There are two principal types of thermocompressors. The first one is steam control device that uses high-pressure steam, referred to as motive steam, to induce flow from a lower pressure steam source and discharge the mixture at an intermediate pressure [1]. The second one is mechanical device which represents cylinder where piston moves and pushes the gas through the regenerator. Regenerator can be external [2] or integrated into displacer. Such regenerators can be wired [3] or annular [4].

This article deals with mechanical thermocompressor with wired regenerator integrated with displacer.

First concept of thermocompressor was introduced by V. Bush in 1939 [5]. Recent studies of thermocompressor are pointed on research of compressor with annular regenerator or thermocompressor operation within different devices. For example, thermocompressor operation as a drive for pulse tube was investigated in [6] and application of thermocompressor for pneumatically actuated ankle-foot orthosis was investigated in [7]. Thermodynamic analysis of thermocompressor with non-ideal component characteristics was made in [3]. However it does not take into account temperature change inside the thermocompressor change. Investigation of the thermocompressor performance with non-isothermal chambers was made in [8]. This research shows significant influence of temperature change on thermocompressor performance.

The results achieved in [8] raise a question of other factors influence on thermocompressor performance. These factors include:

1. Regeneration efficiency.
2. Geometric characteristics (heat exchange area, length of the cylinder which will affect the piston velocity and consequently gas flow velocity).
3. Time factor which will influence by means of working cycle frequency.
4. Dead volume.
5. Application of heat transfer intensifications such as cylinder finning.
6. Non-isothermal conditions of chambers walls.

The influence of first 5 factors is investigated in this article.

Thermocompressor can be used in LNG cryogenic complexes for LNG cold energy utilization during its gasification to obtain an increased gas pressure and decrease costs for its compressing. Cold energy utilization efficiency are described in [9, 10].

2 Physical model of thermocompressor and its operation principle

Physically, considered thermocompressor consists of cylinder with piston-displacer inside. Displacer separates cold chamber from hot chamber. When piston moves in direction of chamber. it pushes the working fluid of this chamber through regenerator into another chamber. Chambers have a different temperatures which causes pressure oscillations due to Amontons's Law. Principal scheme of considered thermocompressor is presented on Figure 1.

Working cycle of thermocompressor starts from high dead centre when both valves are closed and volume of the cold chamber is maximal (point 1). Piston starts to move downside pushing working fluid through regenerator to a hot chamber. Due to Amontons's Law of Pressure-Temperature pressure is increasing because mean temperature of the working fluid inside the thermocompressor is increasing. When the pressure is high enough, output valve opens and working fluid with given pressure starts to be charged to a customer. When piston reaches low dead centre, output valve closes (point 3) and working fluid stops to be charged to a customer.

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Piston starts to move upside pushing working fluid back to a cold chamber. Pressure is decreasing due to decrease of the mean temperature inside the thermocompressor. When pressure drops low enough, input valve opens, charging new portion of working fluid inside the thermocompressor. Working cycle of thermocompressor is presented on Figure 2.

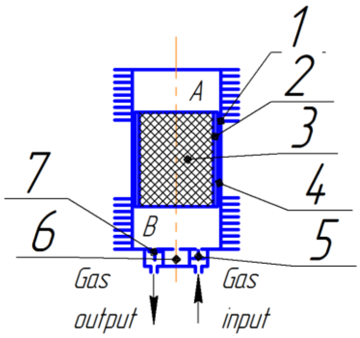

Figure 1. Principal scheme of the mechanical thermocompressor:
1 – thermocompressor shell; 2 – displacer-regenerator shell; 3 – regenerator; 4 – gap; 5 – input valve; 6 – rod; 7 – output valve; A – hot chamber; B – cold chamber.

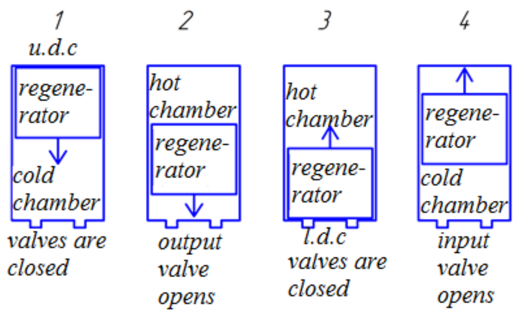

Figure 2. Working cycle of the thermocompressor.

Thermocompressor, investigated in [8] was taken as a prototype for given research. Its characteristics are presented in Table 1.

Table 1. Characteristics of considered thermocompressor.

Parameter	Value
Input pressure, P_{in}	101325
Pressure ratio, π_{tc}	1.5
Cold chamber wall temperature T_{wc}, K	100
Hot chamber wall temperature T_{wh}, K	300
Dead volume of chambers, m^3	$2{,}5 \cdot 10^{-4}$
Displaceable volume, m^3	$5 \cdot 10^{-3}$
Thermocompressor cylinder diameter, m	0.15
Regenerator volume, m^3	$3{,}55 \cdot 10^{-3}$
Frequency, Hz	1
Working fluid	Nitrogen

3 Research of different factors influence

Mathematical model for thermocompressor calculation was presented in [8]. Thermocompressor delivery and arithmetic mean temperature deviations was used as comparison criteria.

3.1 Drive frequency influence on thermocompressor performance

Change of the thermocompressor drive frequency will affect the operation of thermocompressor in different ways. On the one side increase of the working frequency decreases the heat exchange duration and vice versa. One the other side increase of the working frequency increases the velocity of the gas flow and consequently intensify the heat exchange. Also, increase of the frequency causes increases of the friction in regenerator and heating of the gas in both chambers due to this which can cause the thermocompressor overheating, when pressure inside the thermocompressor does not drop below the pressure of input valve opening and input valve does not open. This effect is called choking of thermocompressor.

The results of modelling for frequency range from 0.1 Hz to 5 Hz is presented in table 2.

Table 2. Thermocompressor drive frequency influence on thermocompressor performance.

Frequency f, Hz	TC delivery, W	TC delivery per cycle, J	Temperature deviations	
			Cold chamber ΔT_c, K	Hot chamber ΔT_h, K
0.1	8.74	87.43	3.21	-3.58
0.3	25.79	85.98	3.95	-4.28
0.5	42.58	85.16	4.44	-4.69
1	83.89	83.89	5.1	-5.63
2	164.8	82.39	5.9	-6.68
3	244.2	81.41	6.41	-7.4
5	400.2	80.05	7.51	-7.44

The results of the modelling shows that increase of the working frequency negatively influence thermocompressor delivery in one cycle and temperature deviations. However, this influence is rather small (TC delivery per cycle is decreased on 8.43% but number of cycles is increased in a factor of 50). This causes almost linear dependency of thermocompressor delivery per unit of time of working frequency. It allows to make a conclusion that influence of the working frequency on processes in thermocompressor is negligible and working frequency may be high.

3.2 Geometric characteristics influence of thermocompressor performance

Geometric configuration of thermocompressor will also affect the performance of thermocompressor. Let's consider a thermocompressor with constant displaceable volume. Its geometric configuration then can be determined by one parameters – its diameter.

Geometric characteristics have a two principle factors which will influence thermocompressor performance. The first one is a heat exchange area and increase of the this area causes better heat exchange and better thermocompressor delivery. With constant volume heat exchange area will be determined by sum of side and end surfaces:

$$F_h = \frac{\pi D^2}{4} + \frac{4\pi V_h}{D};$$
$$F_c = \frac{\pi D^2}{4} + \frac{4\pi V_c}{D}. \quad (1)$$

Functions $F_h(D)$ and $F_c(D)$ have a certain minimum which correspond to a minimal heat exchange area. Configuration of thermocompressor must be selected so that diameter of the compressor is differ than diameter which corresponds to a minimal area.

The second factor is connected with increase of the piston velocity with increase of thermocompressor cylinder length. Piston must overcome the longer distance during the same time so piston velocity as well as gas flow velocity increases. Effect of the velocity increase is described above. It should be noted that increase of the cylinder length causes increase of the displacer length because it must separate hot chamber from the cold one.

Together, these factors make a complex effect which is represented in Table 3.

Table 3. Thermocompressor diameter influence on thermocompressor performance.

Diameter D, m	TC delivery, J	Temperature deviations	
		Cold chamber ΔT_c, K	Hot chamber ΔT_h, K
0.05	84.69	4.98	-4.56
0.1	77.44	9.59	-9.38
0.15	73.62	10.5	-12.19
0.18	72.99	10.72	-12.73
0.2	73.1	10.65	-12.73
0.25	74.45	10.03	-11.97
0.3	76.39	10.01	-12.72

A minimal value of compressor delivery can be seen and it is caused by proximity of diameter value to a diameter corresponding to a minimal heat exchange area. This means that first geometric factor makes a more significant influence than a second one. Difference between maximal and minimal values of compressor delivery here is equal to 13.8%. This means that geometric factor must be taken into account during designing of the thermocompressor.

3.3 Regeneration efficiency influence on thermocompressor performance

Regenerator is a key element of thermocompressor. Without it thermocompression is theoretically possible but it would take much longer time. Regenerator efficiency shows the degree of chambers temperature approach to temperatures of the chambers walls. Ideal regeneration means that gas discharging from regenerator will have a temperature equal to a temperature of the corresponding wall. So there will be no heat exchange between gas and walls because there is no temperature difference between them. Ideal regeneration is a primary condition for isothermal model of thermocompressor. Non-ideal regeneration means that gas discharging from regenerator will have a temperature higher (in case of cold chamber) or lower (in case of hot chamber) than temperature of the wall. This will cause temperature change in chambers. The lower regenerator efficiency – the higher temperature difference will be.

Effect of the regeneration efficiency η_{reg} influence on thermocompressor delivery is presented in table 4.

Table 4. Thermocompressor diameter influence on thermocompressor performance.

Diameter D, m	Thermocompressor delivery with regeneration efficiency equal to, J			
	0.8	0.85	0.9	0.95
0.05	47.84	55.43	63.34	71.45
0.1	24.96	36.63	49.23	62.37
0.15	13.65	27.61	43.1	59.38
0.2	11.95	26.27	42.25	59
0.25	15.65	29.34	44.4	60.09
0.3	21.19	33.85	47.53	61.65

Regeneration efficiency is one of the main factors which influence thermocompressor performance. Decrease of the η_{reg} value on 15% (from 95% to 80%) causes losses of delivery equal to 77% in case with diameter equal to 0.15 m. Thermocompressor stops operating properly with low η_{reg} value lower than 70-75%. Designing of the regenerator with high efficiency is a key moment during thermocompressor designing.

3.4 Heat transfer coefficient influence on thermocompressor performance

Heat transfer coefficient change influence the heat exchange intensity between working fluid inside the chambers and its walls (heat exchange in regenerator is determined by regeneration efficiency). Unsurprisingly, the higher value of heat transfer coefficient the more thermocompressor delivery and vice versa. For given research deviation of heat transfer coefficient equal to -

30%. -20%, -10%, 10%, 20% and 30% were investigated. The results of the investigation are presented in Table 5.

Table 5. Thermocompressor diameter influence on thermocompressor performance.

Heat transfer coefficient deviation	TC delivery, J	Temperature deviations	
		Cold chamber ΔT_c, K	Hot chamber ΔT_h, K
0.7α	78.9	7.64	-9.36
0.8α	80.26	6.98	-8.33
0.9α	81.33	6.43	-7.5
1α	82.27	5.96	-6.82
1.1α	83.04	5.56	-6.25
1.2α	83.7	5.2	-5.77
1.3α	84.28	5.15	-5.35

Calculation results are corresponds with prediction made above. However, difference between thermocompressor deliveries on different regime is rather small and during designing more attention must be focused on other issues that heat transfer intensity.

3.5 Dead volume influence on thermocompressor performance

Table 6. Dead volume influence on thermocompressor performance.

Dead volume percentage, %	TC delivery, J	Temperature deviations	
		Cold chamber ΔT_c, K	Hot chamber ΔT_h, K
1	83.47	5.96	-6.82
5	82.27	4.94	-5.66
10	76.91	4.49	-5.01
15	70.75	4.25	-4.54
20	64.29	4.21	-4.39
25	57.69	4.15	-3.77

Dead volume is a volume of the thermocompressor which is not included in displaceable volume. Presence of any dead volume negatively influence the performance characteristics of thermocompressor because dead volume of cold chamber decreases maximal pressure and dead volume of hot chamber increases minimal pressure. Unfortunately, presence of some dead volume is inevitable because it is caused by thermocompressor design elements. For example, volume of gas pockets inside regenerators are dead volume but they are needed for gas passing through regenerator.

Influence of the dead volume (not including regenerator volume) on thermocompressor performance is presented in Table 6. As it can be seen from the table, dead volume almost does not influence temperature change in cold chamber but it significantly influence thermocompressor delivery. The value of dead volume must be kept as low as possible. Together with regeneration efficiency it is one of the most influential factors which affects thermocompressor performance.

3.6 Application of finning for heat exchange intensification

Finning are used in heat engineering for heat exchange intensification. There are two principal types of fins location: lateral (Figure 3) and transverse (Figure 4). Both types of fins serves for increase of the heat exchange area. Transverse fins also forms a flow vortexes between them thus also intensifying heat exchange. However both types of fins add additional dead volume inside cylinder. Calculation of the thermocompressor with both types of fins modelling is presented in Table 7.

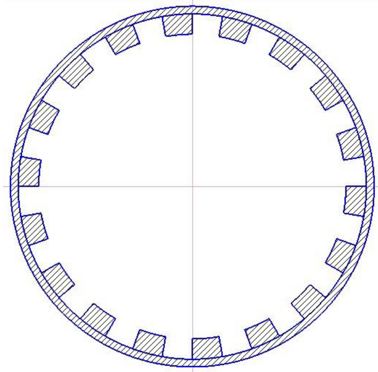

Figure 3. Cross section of thermocompressor with lateral fins

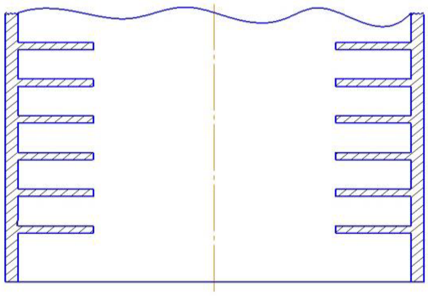

Figure 4. Axial section of thermocompressor with transverse fins

Table 7. Fins application influence on thermocompressor performance.

	Dead volume, m^3	TC delivery, J	ΔT_c, K	ΔT_h, K
No fins	$2.5 \cdot 10^{-4}$	73.6	10.1	-11.1
Lateral	$13.5 \cdot 10^{-4}$	53.1	9.4	-9.1
Transverse	$13.3 \cdot 10^{-4}$	48.7	6.3	-5.8

Calculation shows that fins application positively influence on temperature differences but increase of the dead volume compensates potential raise of compressor delivery. Conclusion can be made that fins application is not suitable for thermocompressor performance enhancement. Lateral fins can be used in case when piston is made with special form which will «streamline» the circuit of fins but manufacturing of such piston is very complicated and thermal expansion must be taken into account.

4 Conclusion

This article deals with estimation of different factors influence on thermocompressor performance. These factors include:

- Regeneration efficiency.
- Thermocompressor diameter.
- Working frequency.
- Dead volume.
- Heat transfer coefficient deviation.
- Fins application.

The two most influential factors are regeneration efficiency and dead volume. Decrease of the regeneration efficiency on 15% can cause decrease of the compressor delivery up to 77% (in case with thermocompressor diameter equal to 0.15 m). Increase of the dead volume percentage from 1% to 20% causes decrease of the compressor delivery equal to 22.98%.

Heat exchange area of the thermocompressor depends on its diameter and this dependency has minimal value. During designing, diameter of the thermocompressor must be chosen in such manner to avoid this minimal value.

Application of fins is not effective way to increase thermocompressor performance because increase of the dead volume due to fin application is more significant factor than intensification of heat exchange. In case of vertical fin, special displacer can be designed which will fill the space between fins, but it leads to a significant complications in displacer design.

The results of this work can be used during thermocompressor design optimization for receiving a better delivery. Optimization will results in operation costs decrease which is important part of energy saving.

Acknowledgement

This work was supported by the Ministry of Education and Science of the Russian Federation in the framework of the implementation of the Program «Research and development on priority directions of scientific-technological complex of Russia for 2014– 2020».

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