Experimental studies of correction propulsion system elements for small space vehicles manufactured due to additive method

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Abstract. Producing ammonia correction propulsion system (CPS) elements for maneuvering satellite platforms (MSP) of small space vehicles (SSV) is a relevant problem. The investigation is devoted to the solution of the named problem with the use of direct metal laser sintering (DMLS) method. The research objective is to confirm the feasibility of manufacturing ETMT and CPS evaporator with autonomous heating elements (AHE) by DMLS method, based on the prototypes experimental testing. During the research the following tasks were solved: creating 3D models for ETMT and double-threaded evaporator and producing experimental prototypes by DMLS method. 3D models of ETMT and evaporator casings were developed following the prototypes produced by the conventional methods of turning and milling. 3D models of ETMT and evaporator casings represent complex integral parts with multiple passages for working medium flow. Experimental studies of ETMT and the evaporator were performed with nitrogen as a working medium. ETMT and evaporator temperature characteristics were determined during the experiments. The investigation was made of ETMT with nominal thrust of 30 mN and power consumption in the range of 5-60 W with and without heat insulation. AHE with embedded thermocouples, having the diameter of 6 mm and power consumption of 60 W, was used. AHE temperature was limited by 973 K. A double-threaded evaporator was investigated for power consumption of 5-30 W, the evaporator casing temperature limited by 393 K. The maximal increase in the gas temperature equaled no more than 8.6 % at the nozzle exit in the power consumption range of 10-60 W for ETMT with heat insulation. At ETMT power consumption of 5–50 W, the build-up time for ETMT was 400–600 s. While at power consumption of 50–60 W, it was 200–400 s. At power consumption of 10–30 W, the evaporator casing temperature reached 393 K in 100–340 s, AHE temperature being 400–460 K and the gas temperature at the evaporator throttle exit being no more than 290 K. At power consumption of 5 W, the maximum evaporator casing temperature of 375 K was reached in 1200 s, AHE temperature being 370 K and the gas temperature at the evaporator throttle exit being no more than 302 K.

1. Introduction
Currently the significance of developing MSP with ammonia CPS and ETMT is becoming increasingly important, since the modern SSV call for completing a wide range of orbital maneuvering challenges: error correction of injection by launch vehicles, maintaining orbital parameters, interorbital maneuvering, construction of SSV orbit groups, injection of SSV into utilization orbit, inspection of other SSV and orbital objects, near-space surveillance and etc. [1–3].
Applying ammonia CPS in SSV is possible due to high specific burst of power for ETMT being achievable at minimal energy consumption. It results in decreased fuel weight necessary to realize target characteristic speed of CPS in SSV during orbital maneuvering, as well as the weight of CPS itself and its means of adaptation in SSV.

Recently constructed ammonia CPS with ETMT were a part of SSV "Ugatusat" (Russia, 2008) with 35 kg weight and SSV "VH-2" (China, 2016) with 47 kg weight. Ammonia CPS were created in Ukraine for SSV "SICH - 2M" (2011–2012) and SSV "Microsat".

In such CPS the ammonia becomes gaseous due to its preliminary gasification in the evaporator and final heating in ETMT.

The developed ammonia ETMT with 30 mN thrust are characterized by the cost of thrust up to 2 W/mN and are used as components in SSV with weight of 30–400 kg. The specific burst of power for such ETMT at energy consumption of 60 W is not higher than 250 s. Due to their structure, they can be classified as ETMT with tubular heating element (THE) and ETMT with AHE (figures 1,2) [1–3,10].

![Figure 1. Schematics of ETMT with AHE.](image1)

![Figure 2. Schematics of ETMT with THE.](image2)

The known ETMT represent complex constructions with inner cavities and gas ducts, for example, as shown in figure 3 [1–9].
In terms of design ETMT with AHE can be divided into AHE and ETMT casing, that are manufactured separately (figures 1, 4, 5).

1 - AHE; 2 - fuel inlet and attachment node; 3 - casing with nozzle and gas flow conditioner (located inside).

**Figure 3.** J3 concentric tubular resistojet schematics.

**Figure 4.** Mark-III, Mark-IY microthrusters schematics.

**Figure 5.** ETMT with AHE, manufactured by turning and milling.

The conventional method of manufacturing ETMT casing consists of milling and turning its individual parts and forming various cavities and gas ducts. The components are sealed by welding after the casing assembly. Stainless steel 12X18H10T is used as a constructional material. All this results in additional flange joints appearance and ETMT casing walls thickening due to technological characteristics and incorporated equipment limitations. Moreover, technological constraints preclude one from manufacturing inner gaseous cavities and flanges necessary for ETMT optimal performance.
A liquefied ammonia evaporator used in ammonia CPS production also includes AHE and a separate casing (figure 6).

Figure 6. Double-threaded liquefied ammonia evaporator.

The example setups for ETMT and the evaporator with AHE as a part of CPS automatic equipment are given in figure 7.

Figure 7. ETMT and liquefied ammonia evaporator with AHE as a part of CPS reserved automatic equipment (a) and unreserved one (b).

Manufacturing AHE and ETMT casing separately allows modern additive methods to be applied to ETMT casing production, this casing being a complex construction with gas ducts and inner cavities.

2. Problem statement
The research objective is to determine whether it is possible to produce ETMT with AHE and the evaporator with AHE, both being a part of the ammonia CPS, following the additive technique based on direct metal laser sintering (DMLS) method.

To solve the task at hand:

- 3D models of ETMT and the evaporator were developed;
- ETMT and the evaporator were produced by DMLS method;
- experimental tests on ETMT and the evaporator with AHE were performed in a vacuum chamber during operation on nitrogen.

Electrical testing of ETMT in the power consumption range of 5-60 W was carried out to study:
- ETMT heating dynamics at working medium feeding in the vacuum chamber (cold starting method) without heat insulation;
- ETMT heating dynamics at working medium feeding in the vacuum chamber (cold starting method) with heat insulation.

A cylindrical electric heater with two thermocouples was used as AHE, its specifications are:
- nominal power capacity, 60 W;
- working voltage, 12 W;
- diameter, 6.0 mm;
- length, 80 mm;
- weight, 0.03 kg.

To lower heat loss in ETMT, multi-layer heat insulation was used. It was placed into a cylindrical jacket made of composite material, consisting of fabrics HVK-0.05, foil, alloy BD3D, 8 μm.

Evaporator electrical testing was conducted to study the temperatures of AHE, the evaporator casing and the gas at the exit for power consumption of 5–30 W. The maximum temperature of the evaporator casing was maintained at 393 K. This constraint was introduced following the temperature limitations of the pressure controller.

3. Theory

When producing ETMT casing and the evaporator, direct metal laser sintering (DMLS) method was used, this method being widespread in 3D printing of metal products. DMLS is an additive process allowing ETMT casing and the evaporator to be built up gradually layer by layer.

Usually DMLS calls for production of supporting elements which are deleted after the printing. These elements provide the precision of ETMT and evaporator casing and no rigid component parts, considering the thermal processes during melting. All surfaces with the ground plane angle less than 45° are supported. Moreover the ratio of the walls height to their thickness should be maintained within 8:1.

To avoid unnecessary supports, smooth transitions are introduced in 3D model of ETMT and the evaporator. Sharp edges were also rounded at the joints of the walls and inner elements.

3D model of ETMT is constructed in such a way that a single casing includes nozzle, outer casing, inner casing with gas ducts in the double-start thread form, gas flow conditioner and microthruster attachment point (figures 8, 9). 3D model of the evaporator casing (figure 10) is constructed in a similar way.

Figure 8. 3D model of ETMT casing.

Figure 9. Production prototype of ETMT with AHE.
1 - gas ducts; 2 - crosscut working medium inlets/outlets (two variants are provided); 3, 4 - axial working medium inlets/outlets; 5 - AHE

Figure 10. 3D model and production prototype of evaporator.

Production prototype of the evaporator assembled with the pressure controller is shown in figure 11.

Figure 11. Production prototype of evaporator with pressure controller.

Technological characteristics of manufacturing ETMT casing by the additive technique compared to manufacturing ETMT casing by turning and milling component parts are given in table 1. The evaporator has similar technological characteristics.

Table 1. Technological characteristics of manufacturing ETMT casing.
### Characteristics of Manufacturing Technique for ETMT Casing

| №  | Description                                      | Turning, milling | Additive, DMLS |
|----|--------------------------------------------------|------------------|---------------|
| 1  | The number of parts in ETMT casing               |                  |               |
| 2  | Gas ducts, fittings and joints sealing provision| Gas migration is possible among cavities | Is provided |
| 3  | The possibility of manufacturing any inner cavities, flanges | Is not provided | Is provided |
| 4  | The possibility of manufacturing thin-walled shells | Technological constraints are available | Technological constraints are minimal |
| 5  | The possibility of machining inner cavities       | Is available     | Is not available, except nozzle part |
| 6  | The achieved ETMT casing weight                  | 25               | 22            |
| 7  | The possibility of lowering ETMT casing weight    | Technological constraints are available | Technological constraints are minimal |

ETMT experimental studies were performed in the vacuum chamber (figure 11). To document the outflowing gas temperature, a thermocouple was installed at ETMT nozzle exit.

**Figure 11.** Installing ETMT in the vacuum chamber (a) without heat-protective cover (b) and with it (c).

Pneumatic-hydraulic diagram of the experimental installation with the vacuum chamber in ETMT testing is given as shown in figure 12.

**Figure 12.** Pneumatic-hydraulic diagram of the experimental installation.

ETMT electrical tests were performed with heat insulation as well as without one. To lower heat loss in ETMT, multi-layer heat insulation was used, placed in a heat-protective cover from composite material, consisting of fabrics HVK-0.05 TU 6-48-05-786904-151-95, foil, alloy BD3D, 8 μm TU 48-21-151-84.
Cold starting method was used at ETMT (and evaporator) testing, which means that voltage supply and working medium feeding to ETMT (and evaporator) were performed simultaneously. When testing the evaporator, pneumatic-hydraulic diagram similar to the one in figure 12 was used. The evaporator was connected to the pressure controller, and the throttle imitating ETMT was installed instead of ETMT. The thermocouples measured the temperatures of the gas at the throttle exit and of the evaporator casing. AHE temperature was measured by the embedded thermocouples.

![Figure 13. Installing the evaporator in the vacuum chamber.](image)

4. Experimental results
The study subjects were ETMT and the evaporator, produced by DMLS method. More than 12 evaporator and ETMT casings were manufactured. All resulting casing samples were characterized by geometric shapes stability, the nozzle included. All minor shape roughness was removed by machining (figure 14).

![Figure 14. Production prototypes of the evaporator and ETMT casings.](image)

The inner nozzle surface can be refined as well, if necessary. All ETMT and evaporator casings were inspected for integrity and gas permeability. Deviations in integrity and throats were not found. When welding was used during ETMT and the evaporator assembly, the material resulting from DMLS method possessed good weld ability.

The experimental testing results for the temperatures of AHE and the gas at ETMT nozzle exit during cold starting method (without preheating) are given in figures 15–18 and tables 2–5.
Figure 15. The dependence of AHE temperature on the heating time for ETMT without a heat-protective cover at various values of supplied power with AHE heating temperature limited by 973 K.

Figure 16. The dependence of the gas temperature at the nozzle exit on the heating time for ETMT without a heat-protective cover at various values of supplied power with AHE heating temperature limited by 973 K.

Figure 17. The dependence of AHE temperature on the heating time for ETMT with a heat-protective cover at various values of supplied power with AHE heating temperature limited by 973 K.
Figure 18. The dependence of the gas temperature at the nozzle exit on the heating time for ETMT with a heat-protective cover at various values of supplied power with AHE heating temperature limited by 973 K.

Table 2. The temperature of AHE and the gas at the nozzle exit for ETMT without heat insulation with AHE heating temperature limited by 973 K.

| τ, s | The temperature of AHE (1) and the gas at the nozzle exit (2), K for various values of power, W |
|------|--------------------------------------------------------------------------------------------------|
|      | W =5 W | W =10 W | W =20 W | W =30 W | W =40 W | W =50 W | W =60 W |
| 0    | 291    | 287    | 290    | 287    | 289    | 286    | 284    | 282    | 291    | 288    | 297    | 289    | 298    | 289    |
| 100  | 343    | 295    | 388    | 306    | 475    | 323    | 551    | 337    | 623    | 352    | 704    | 366    | 787    | 379    |
| 200  | 363    | 307    | 424    | 327    | 544    | 361    | 646    | 385    | 738    | 406    | 841    | 424    | 941    | 442    |
| 300  | 375    | 315    | 446    | 341    | 584    | 384    | 702    | 413    | 797    | 435    | 905    | 454    |        |        |
| 400  | 384    | 321    | 461    | 351    | 610    | 399    | 734    | 429    | 831    | 449    | 933    | 467    |        |        |
| 500  | 390    | 325    | 471    | 358    | 626    | 408    | 752    | 438    | 850    | 457    | 946    | 472    |        |        |
| 600  | 394    | 328    | 478    | 362    | 637    | 413    | 763    | 442    | 859    | 460    | 952    | 474    |        |        |
| 700  | 397    | 330    | 483    | 366    | 644    | 417    | 769    | 445    | 865    | 462    | 955    | 475    |        |        |
| 800  | 399    | 332    | 487    | 368    | 649    | 419    | 773    | 446    | 868    | 463    | 956    | 475    |        |        |
| 900  | 401    | 333    | 490    | 369    | 653    | 420    | 776    | 447    | 870    | 463    | 955    | 475    |        |        |
| 1000 | 403    | 334    | 493    | 371    | 656    | 421    | 778    | 447    | 872    | 463    | 954    | 475    |        |        |
| 1100 | 404    | 335    | 494    | 372    | 658    | 422    | 779    | 448    | 873    | 464    | 953    | 475    |        |        |
| 1200 | 405    | 335    | 496    | 373    | 659    | 423    | 780    | 449    | 874    | 465    | 954    | 476    |        |        |
Table 3. The temperature of AHE and the gas at the nozzle exit for ETMT with heat insulation with AHE heating temperature limited by 973 K.

| \( \tau \), s | \( W = 5 \) W | \( W = 10 \) W | \( W = 20 \) W | \( W = 30 \) W | \( W = 40 \) W | \( W = 50 \) W | \( W = 60 \) W |
|---|---|---|---|---|---|---|---|
| 0 | 297 | 291 | 296 | 292 | 300 | 291 | 295 | 292 | 299 | 291 | 285 | 289 | 300 | 291 |
| 100 | 339 | 297 | 380 | 308 | 474 | 334 | 556 | 353 | 634 | 369 | 703 | 379 | 793 | 394 |
| 200 | 356 | 307 | 413 | 329 | 540 | 372 | 650 | 401 | 756 | 423 | 852 | 438 | 956 | 458 |
| 300 | 368 | 315 | 435 | 343 | 581 | 395 | 705 | 429 | 830 | 455 | 930 | 472 |
| 400 | 375 | 320 | 450 | 352 | 608 | 41 | 743 | 447 | 874 | 475 |
| 500 | 381 | 324 | 461 | 359 | 627 | 421 | 771 | 460 | 901 | 488 |
| 600 | 385 | 327 | 469 | 365 | 642 | 429 | 786 | 468 | 916 | 496 |
| 700 | 389 | 329 | 476 | 369 | 652 | 435 | 799 | 474 | 923 | 501 |
| 800 | 391 | 331 | 481 | 372 | 660 | 439 | 807 | 478 | 927 | 505 |
| 900 | 394 | 332 | 484 | 374 | 666 | 442 | 811 | 481 | 929 | 507 |
| 1000 | 395 | 334 | 487 | 376 | 673 | 445 | 812 | 483 | 934 | 508 |
| 1100 | 397 | 334 | 491 | 378 | 675 | 447 | 811 | 483 | 939 | 509 |
| 1200 | 400 | 335 | 495 | 379 | 675 | 448 | 817 | 484 | 940 | 509 |

Table 4. The temperature of AHE for ETMT without heat insulation and with it with AHE heating temperature limited by 973 K.

| \( \tau \), s | \( W = 5 \) W | \( W = 10 \) W | \( W = 20 \) W | \( W = 30 \) W | \( W = 40 \) W | \( W = 50 \) W | \( W = 60 \) W |
|---|---|---|---|---|---|---|---|
| 0 | 291 | 297 | 290 | 296 | 289 | 300 | 284 | 295 | 291 | 299 | 285 | 298 | 300 |
| 100 | 343 | 339 | 388 | 380 | 475 | 474 | 551 | 556 | 623 | 634 | 704 | 703 | 787 | 793 |
| 200 | 363 | 356 | 424 | 413 | 544 | 540 | 646 | 650 | 738 | 756 | 841 | 852 | 941 | 956 |
| 300 | 375 | 368 | 446 | 435 | 584 | 581 | 702 | 705 | 797 | 830 | 905 | 930 |
| 400 | 384 | 375 | 461 | 450 | 610 | 608 | 734 | 743 | 831 | 874 |
| 500 | 390 | 381 | 471 | 461 | 626 | 627 | 752 | 771 | 850 | 901 |
| 600 | 394 | 385 | 478 | 469 | 637 | 642 | 763 | 786 | 859 | 916 |
| 700 | 397 | 389 | 483 | 476 | 644 | 652 | 769 | 799 | 865 | 923 |
| 800 | 399 | 391 | 487 | 481 | 649 | 660 | 773 | 807 | 868 | 927 |
| 900 | 401 | 394 | 490 | 484 | 653 | 666 | 776 | 811 | 870 | 929 |
| 1000 | 403 | 395 | 493 | 487 | 656 | 673 | 778 | 812 | 872 | 934 |
| 1100 | 404 | 397 | 494 | 491 | 658 | 675 | 779 | 811 | 873 | 939 |
| 1200 | 405 | 400 | 496 | 495 | 659 | 675 | 780 | 817 | 874 | 940 |
**Table 5.** The temperature of the gas at the nozzle exit for ETMT without and with heat insulation with AHE heating temperature limited by 973 K.

| τ, s | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
|------|---|---|---|---|---|---|---|---|---|---|---|---|
|      | W =5 W | W =10 W | W =20 W | W =30 W | W =40 W | W =50 W | W =60 W |
| 0    | 287 | 291 | 287 | 292 | 286 | 291 | 282 | 292 | 288 | 291 | 289 | 291 |
| 100  | 295 | 297 | 306 | 308 | 323 | 334 | 337 | 353 | 352 | 369 | 366 | 379 | 379 |
| 200  | 307 | 307 | 327 | 329 | 361 | 372 | 385 | 401 | 406 | 423 | 424 | 438 | 442 |
| 300  | 315 | 315 | 341 | 343 | 384 | 395 | 413 | 429 | 435 | 455 | 454 | 472 |   |
| 400  | 321 | 320 | 351 | 352 | 399 | 41 | 429 | 447 | 449 | 475 |   |   |   |
| 500  | 325 | 324 | 358 | 359 | 408 | 421 | 438 | 460 | 457 | 488 |   |   |   |
| 600  | 328 | 327 | 362 | 365 | 413 | 429 | 442 | 468 | 460 | 496 |   |   |   |
| 700  | 330 | 329 | 366 | 369 | 417 | 435 | 445 | 474 | 462 | 501 |   |   |   |
| 800  | 332 | 331 | 368 | 372 | 419 | 439 | 446 | 478 | 463 | 505 |   |   |   |
| 900  | 333 | 332 | 369 | 374 | 420 | 442 | 447 | 481 | 463 | 507 |   |   |   |
| 1000 | 334 | 334 | 371 | 376 | 421 | 445 | 447 | 483 | 463 | 508 |   |   |   |
| 1100 | 335 | 334 | 372 | 378 | 422 | 447 | 448 | 483 | 464 | 509 |   |   |   |
| 1200 | 335 | 335 | 373 | 379 | 423 | 448 | 449 | 484 | 465 | 509 |   |   |   |

Experimental testing results for the evaporator are given in figures 19–21.

**Figure 19.** The dependence of AHE temperature on the heating time for various values of supplied power with the casing heating temperature limited by 393 K.
5. Results and discussion

Applying DMLS method to ETMT manufacturing allowed the following components to be incorporated in one part: outer casing, inner casing with gas ducts in double-start thread form, gas flow conditioner and microthruster attachment point. Therefore, the number of the parts manufactured for ETMT was reduced from 5 to 1, and for the evaporator from 3 to 1. In addition, it is possible to manufacture any inner cavities and flanges.

The analysis of the diagrams in figures 15–18 as well as tables 2–5 showed that at the limited heating temperature for ETMT AHE of 973 K:

- the effect of heat insulation on AHE temperature increase starts at ETMT power consumption of 20 W;
- the maximal increase in AHE temperature in power consumption range of 20–60 W for ETMT with heat insulation is no more than 7 %;
- the effect of heat insulation on the gas temperature increase at the nozzle exit starts at ETMT power consumption of 10 W;
- the maximal increase in the gas temperature equaled no more than 8.6 % at the nozzle exit in the power consumption range of 10–60 W for ETMT with heat insulation;
- the dynamics of ETMT entering the stationary mode largely depends on ETMT power consumption;
- at ETMT power consumption of 5–50 W, the build-up time for ETMT was 400–600 s;
- at power consumption of 50–60 W, the build-up time for ETMT was 200–400s.

The analysis of the diagrams in figures 19–21 showed that at the evaporator casing heating temperature limited by 393 K:

![Figure 20](image.png)

**Figure 20.** The dependence of the gas temperature at the evaporator throttle exit on the heating time for various values of supplied power with the casing heating temperature limited by 393 K.

![Figure 21](image.png)

**Figure 21.** The dependence of the evaporator casing temperature on the heating time at various values of supplied power with AHE heating temperature limited by 973 K.
at power consumption of 10–30 W the evaporator casing temperature of 393 K is reached in 100-340 s, in addition AHE temperature is 400–460 K and the gas temperature at the evaporator throttle exit is no more than 290 K;

at power consumption of 5 W, the maximum evaporator casing temperature of 375 K is reached in 1200 s, AHE temperature being 370 K and the gas temperature at the evaporator throttle exit being no more than 302 K.

The comparison of the resulting temperature characteristics for ETMT and the evaporator manufactured due to the additive technique with the similar characteristics for ETMT and the evaporator manufactured by the conventional method detected no key differences.

6. Conclusion
1. The possibility of producing ETMT and evaporator casings for SSV CPS by direct metal laser sintering (DMLS) method was experimentally proved, moreover:
   - ETMT and evaporator casings are manufactured as an individual part with gas ducts inside;
   - all manufactured casing prototypes feature stable geometric shapes;
   - the casing material is characterized by integrity and weldability.
2. The results of the undertaken experimental testing point out full operational capability of ETMT and the evaporator. ETMT and evaporator temperature characteristics correspond to the prototypes manufactured by the conventional method (turning and milling).
3. Direct metal laser sintering (DMLS) method allows one to create new designs for ETMT and the evaporator with optimal parameters of gas ducts in terms of quantity and geometry, including the passages to measure pressure (temperature), these being hard or impossible to make with conventional manufacturing methods (turning and milling) (figure 22).

![Figure 22. Resulting experimental ETMT with a passage to measure pressure (temperature) at the entry of the nozzle throat.](image-url)

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