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# Adsorption system with two-phase heat exchanger for effective accumulation and safe storage of gaseous fuel

*Leonard L.Vasiliev, L.E. Kanonchik, M.I. Rabetsky*

**Porous media laboratory, Luikov Heat & Mass Transfer Institute, National Academy of Science of BELARUS**

# ABSTRACT


- Numerical results are presented for the low-pressure storage tank, packed with activated carbon fibrous material and furnished a thermosyphon heat exchanger and gas inlet and outlet tubes for recirculation loop.
- Two designs of novel thermosyphon with long horizontal evaporators were developed for sorbent bed cooling and heating: a loop thermosyphon with porous coating of the evaporator annular channel (LTPE), and vapordynamic thermosyphon (VDT) with wickless annular channels in the evaporator and condenser.
- The use of a green natural gas will improve the ecology of cities and lead to a qualitatively new solution of energy supply. Two promising technologies that are found to be useful for such a case are the application of heat pipes (thermosyphons) and adsorbed natural gas (ANG).

# ADVANTAGES OF ADSORPTION GAS STORAGE TECHNOLOGY

- Energy saving, ecological cleanness
- Low pressure (2-6 MPa) in the non-cylindrical container
- Low capital and operating cost of compression and refueling equipment
- Flexibility in configuration and placement design
- Lower cylinder weight, application of fiber-glass and black-reinforced plastics as the gas tank envelope

✓ **Active carbon fibrous material-effective storage medium for the most current gases**

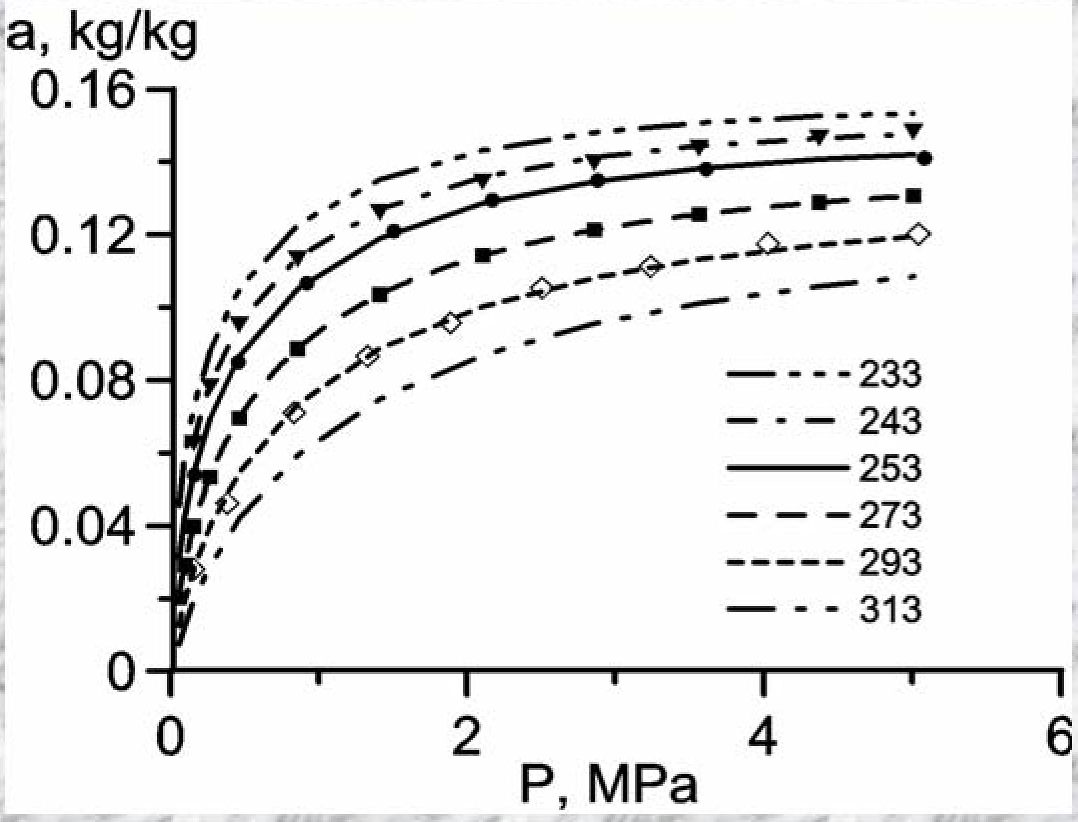
✓ **Heat pipes and thermosyphons are the most perspective thermal control devices for the adsorption system.**

# Part 1

- Introduction
- Modeling of the gas charging device
- Gas tank and scheme of its recirculation charging
- Gas tank using both passive and active thermal control in the sorbent bed

# Isotherms of methane adsorption on Busofit-type ACF

$$a_{eq} = W_0 \rho_b \exp\left\{ -\left\{ \left[ \frac{RT}{E} \ln\left( \frac{P_{cr}}{P} \cdot \left( \frac{T}{T_{cr}} \right)^2 \right) \right]^n + \alpha_{t,mod}(T - T_b) \right\} \right\}$$




The parameters for the initial adsorption isotherm were obtained by the least square fit of the adsorption model to the experimental data

**$T_0$=243.15 K; $(R/E)^2$=0.97 $10^{-6}$**

**$W_0 r_b = a_0$=0.149 kg/kg, n=2**

*Points - experiment;*
*lines - calculation (Eq. 14)*

# CFD model of HP-cylinder/adsorber

- the energy equation

$$\frac{\partial}{\partial\tau}\left(\varepsilon\rho_g E_g+(1-\varepsilon)\rho_s^* E_s\right)+\nabla\left(\vec{v}\left(\rho_g E_g+P\right)\right)=\nabla\left(\lambda_{ef}\nabla T\right)+S_H$$

- the equation of continuity

$$\frac{\partial\varepsilon\rho_g}{\partial\tau}+\nabla\left(\rho_g\vec{v}\right)=S_m;$$

$$S_{\mathrm{m}}=\left(\varepsilon_t-1\right)\rho_{\mathrm{s}}M_{\mathrm{g}}\frac{\partial N}{\partial\tau}$$

$$\varepsilon_t=1-\rho/\rho_s$$

$$\varepsilon_t=\varepsilon_\mu+\varepsilon$$

- the equation of momentum balance

$$\frac{\partial}{\partial\tau}\left(\rho_g\vec{v}\right)+\nabla\cdot\left(\rho_g\vec{v}\vec{v}\right)=-\nabla P+\nabla\cdot\left(\bar{\bar{\tau}}_{st}\right)+\vec{F}$$

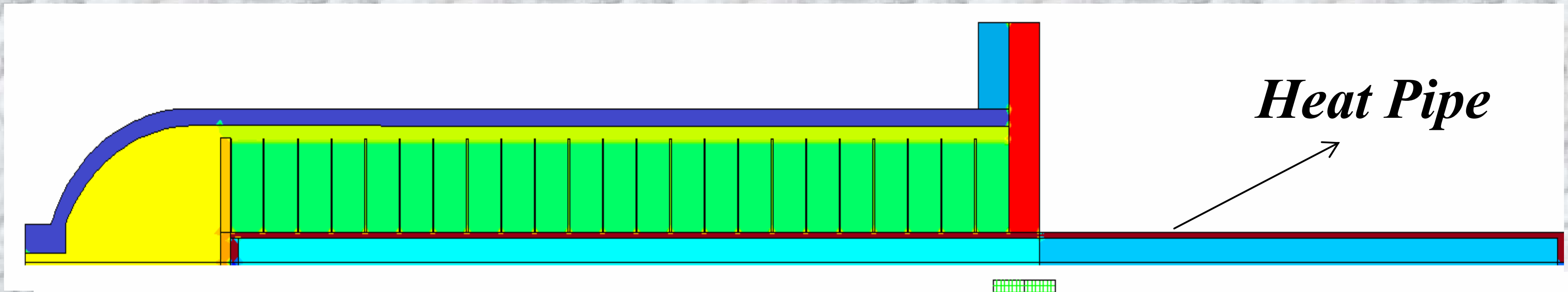
$$S_{\mathrm{H}}=q_{st}S_m/M_{\mathrm{g}}$$

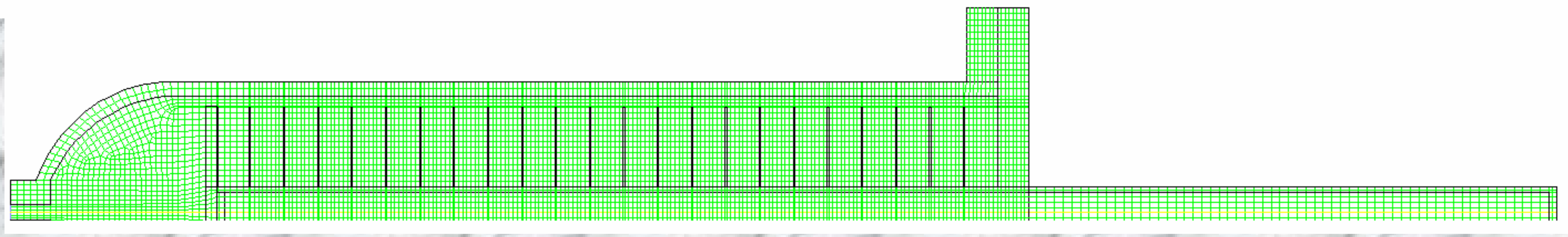
- the equation of kinetic of sorption and modified Dubinin-Astakhov equation of the state of gas

$$\frac{\partial N}{\partial\tau}=K_{s0}\exp\left(-\frac{E}{RT}\right)\left(N_{eq}-N\right);$$

$$N_{eq}=N_0^0\exp\left\{-\left(\frac{A}{E}\right)^2-\alpha_{t,\mathrm{mod}}(T-T_0)\right\}$$

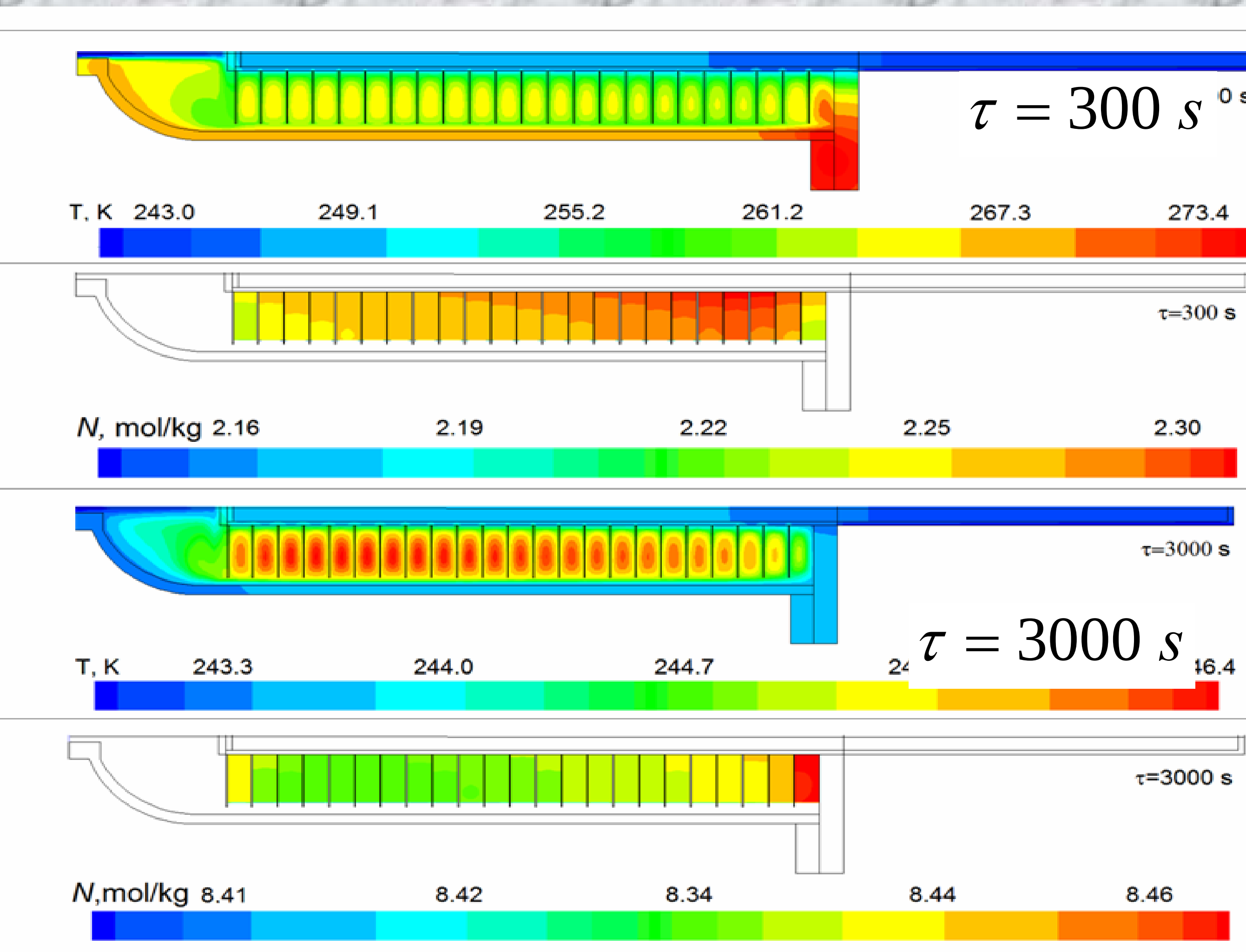
# . Schematic of the computational domain and mesh for the cylinder using HP thermal control



■ ) cylinder casing; ■ ) annular gas channel, formed by the perforated tube and the cylinder casing; ■) adsorbent; ■) HP envelope (outer diameter 0,02 m);
■) vapor channel of HP; ■) free gas volume located before the adsorbent bed; ■) HP fins; ■) flange of the HP suspension; ■) ■) flanges of the cylinder

*2D axisymmetrical mesh geometry for the half-cylinder has been handled*
*The grid consists of quadrilateral 6749 cells and 8432 nodes*



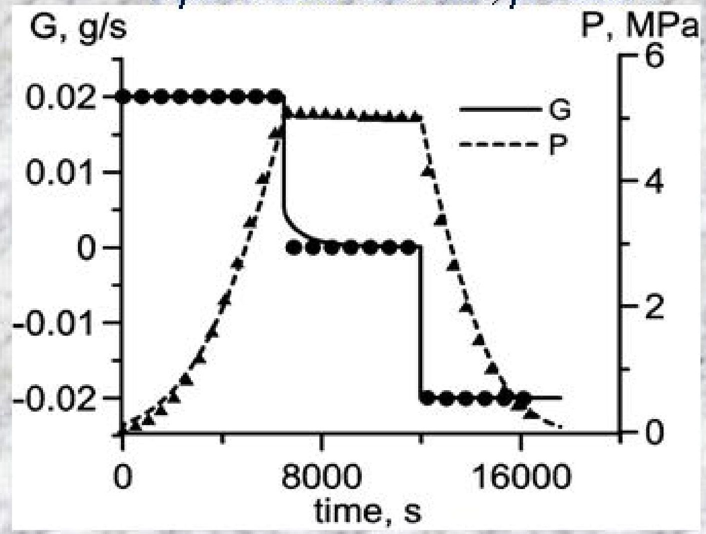

**2D surfaces of temperature and specific amount of adsorbed molecules during of methane charging after 300 s and 3000 s for vessel with finned HP**

- $T_{hp}$ = 243 K;
- $a_{env}$= 50 W/(m$^2$K)
- $T_{env}$= 243 K

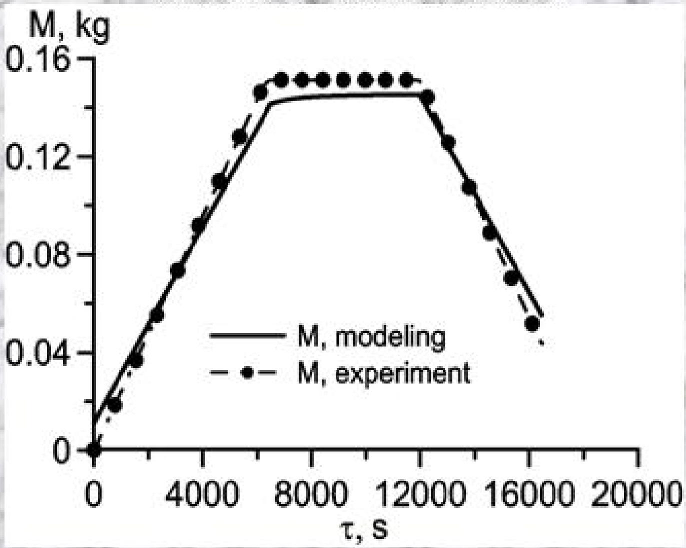
The application of HP or TS in gas storage systems enables one to control the temperature of sorbent bed and provide optimum operational conditions

# Comparison of the results of CFD-moleling and experiment for total cycle of the thermally regulated test vessel

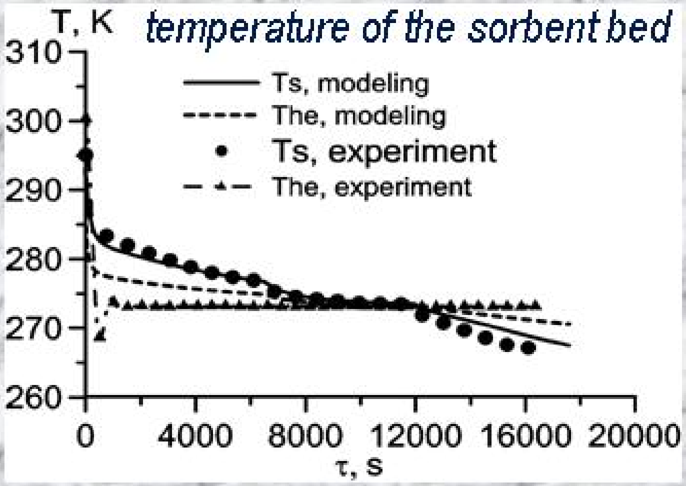
*Input mass flow rate, pressure*




*mass of stored methane*



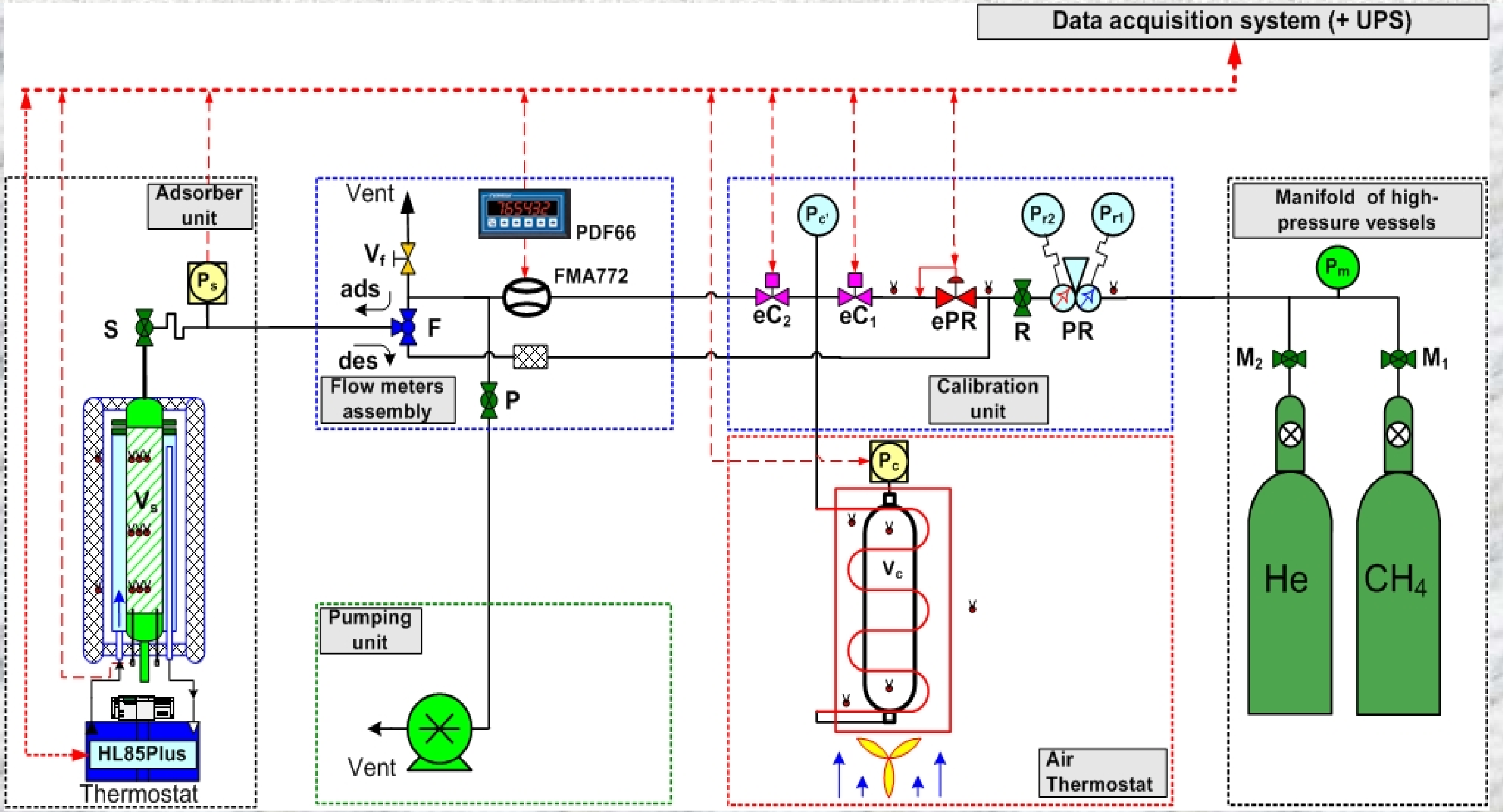

*temperature of the sorbent bed*




- $T_{he}$ = 273 K; • $\alpha_{he}$= 500 W/(m$^2$K)
- HEE (thickness fins 5 mm, spacing 13 mm

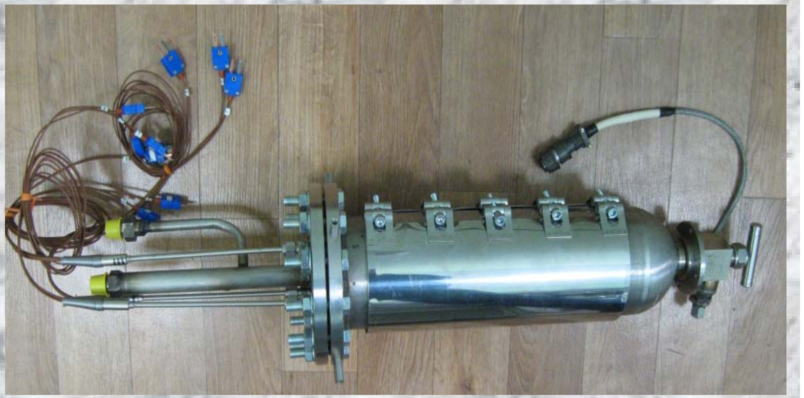
*Real experimental data and data obtained by the model have difference not more than 10—15 %*

# Schematic diagram of the experimental setup

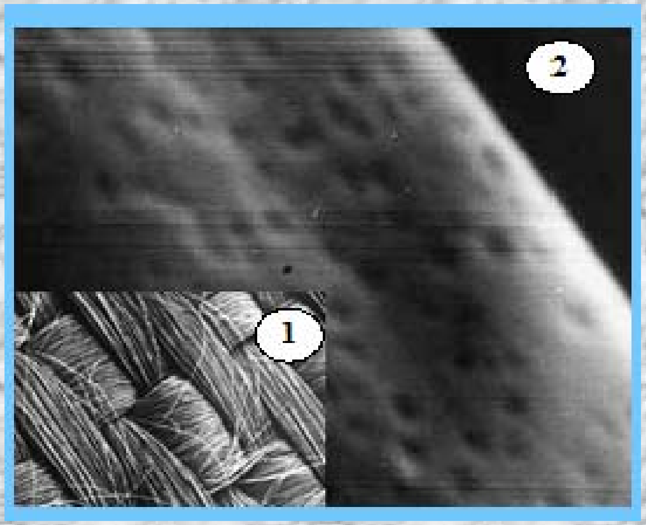



● block for holding high-pressure cylinders (~20 MPa) with tested gases;
● calibrating unit ensuring preliminary storage of a specified amount of
tested gas; ● block of flow meters; ●vacuum pumping block;
● block of

# Adsorbent/filler and test cylinder with temperature sensors and heater installed



The test cylinder (interior volume 2.2 L)
is equipped with a double-pipe heat
exchanger and a thermostatic system.
A separate detachable electric




*It is fabricated in Belarus from impregnated cellulose*

**Fibrous activated carbon based on commercially available "Busofit TM-055“.**

***(It was compressed, bed density - 484 $kg/m^3$ ):***

- ✓ **amount of adsorbent/filler - 679.3 g**
- ✓ **high specific DR-surface 2411 $m^2/g$**
- ✓ **DR-volume of micropores 0.86 ml/g**
- ✓ **uniform surface pore distribution (0.6-2 nm)**

# *Part 2*

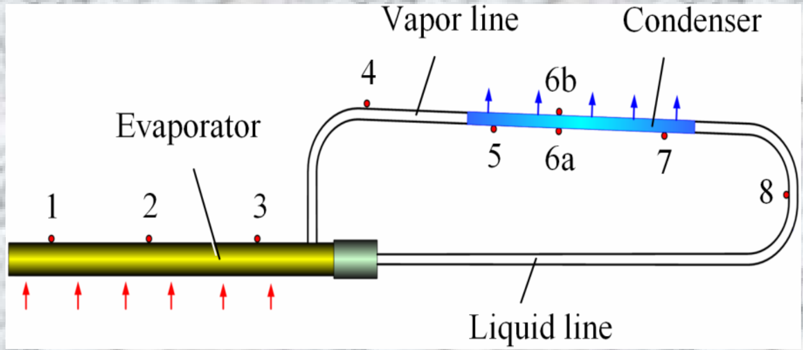
- **Horizontal Loop thermosyphon (LTCE) with porous coating of the evaporator for the ANG tank cooling**

# Introduction

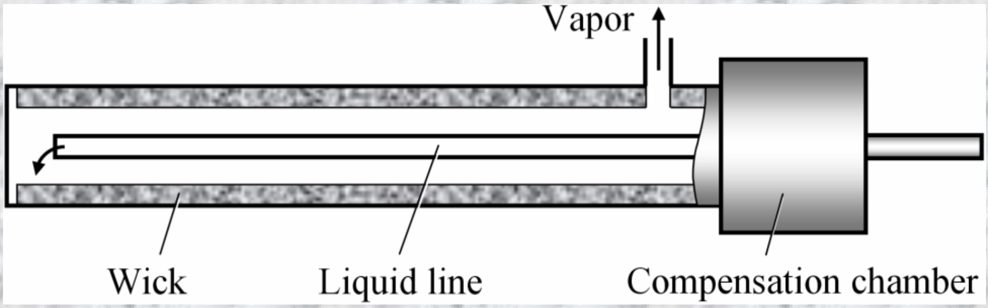
A new loop thermosyphon with porous coating of the horizontal evaporator and smooth horizontal condenser (LTCE) was designed for sorbent bed cooling applications and tested in a large temperatures and heat loads range.

LTCE ensures a shortened start-up time, decreases the evaporator wall temperature, has small hysteresis during the increasing/decreasing of the heat load and suppresses the temperature instability to compare with conventional loop heat pipes (LHP) and loop thermosyphons (LT). The thermal resistance R of LTCE does not exceed 0.36 K/W (R of the evaporator is 0.05 - 0.1 K/W).

# LTCE shematique, longitudinal cross of the evaporator and its dimensions




LTCE with cylindrical horizontally disposed evaporator and condenser; 1-8 thermocouples position on the thermosyphon.

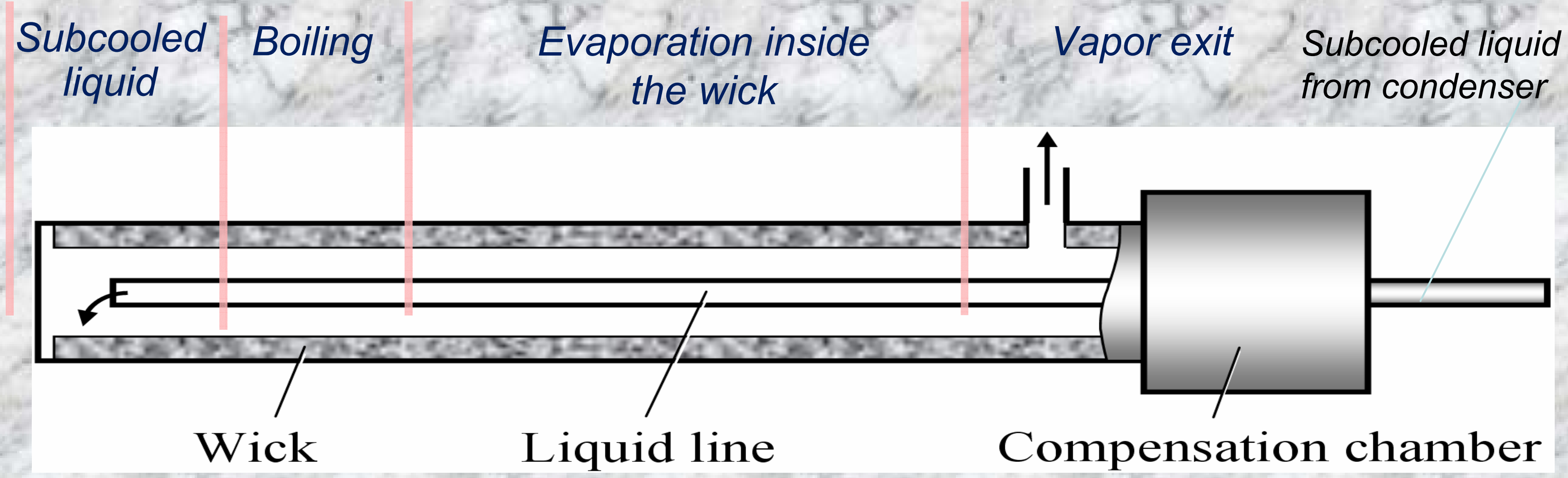


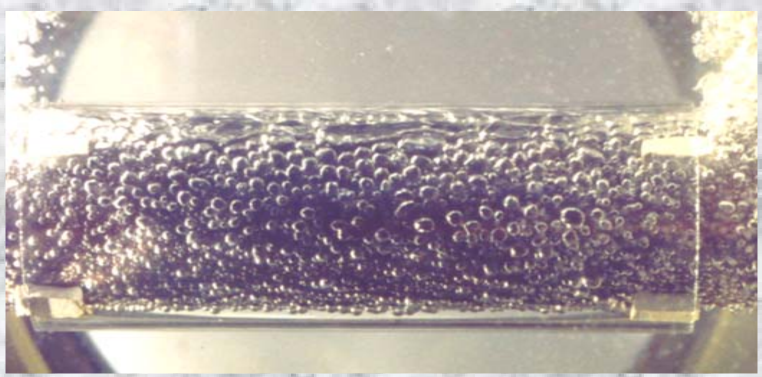

Longitudinal-section of the LTCE evaporator with porous coating

***Table 1. Dimensions of the LTCE components, mm.***

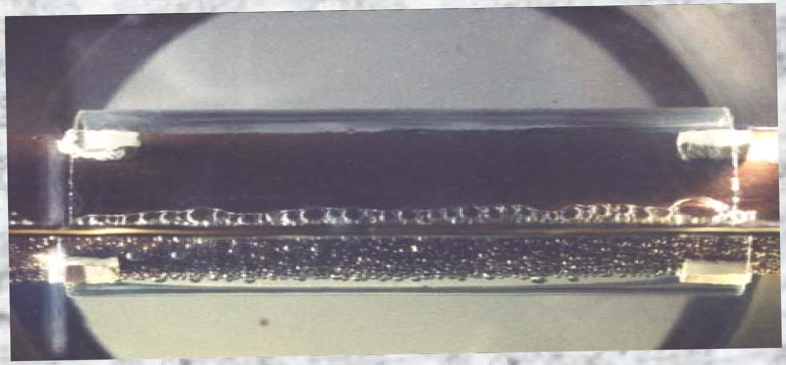
| | |
|---|---|
| **Length of the evaporator** | **130** |
| **Diameter/wall thickness of the evaporator** | **12/1** |
| **Length of the condenser** | **105** |
| **Diameter/wall thickness of the condenser** | **4/0.5** |
| **Length of the vapor line** | **90** |
| **Diameter/wall thickness of the vapor line** | **4/0.5** |
| **Length of the liquid line** | **350** |
| **Diameter/wall thickness of the liquid line** | **3/0.5** |

# Two-phase flow pattern visualization of LTCE evaporator with microporous coating



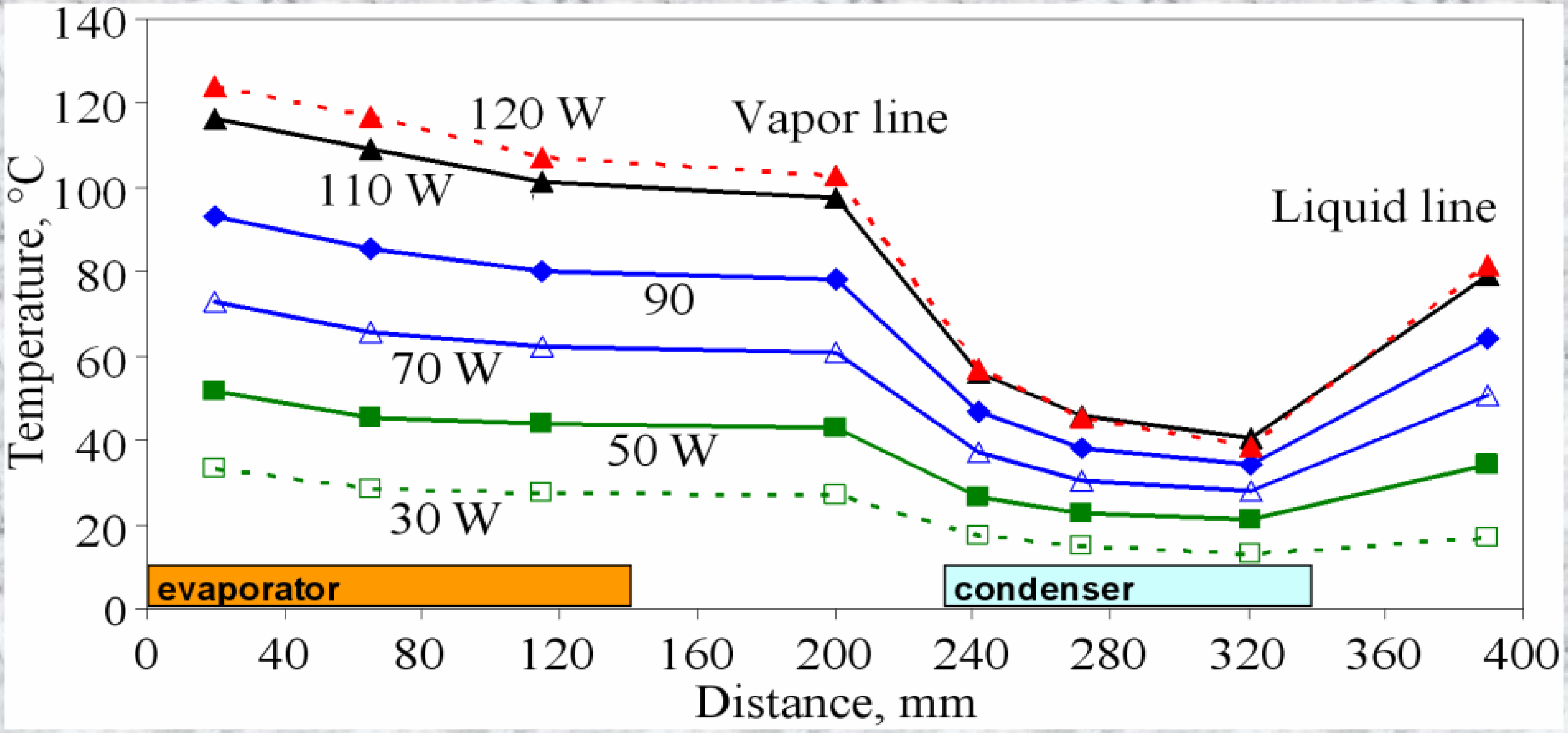



*Bubble flow, boiling on the wick*



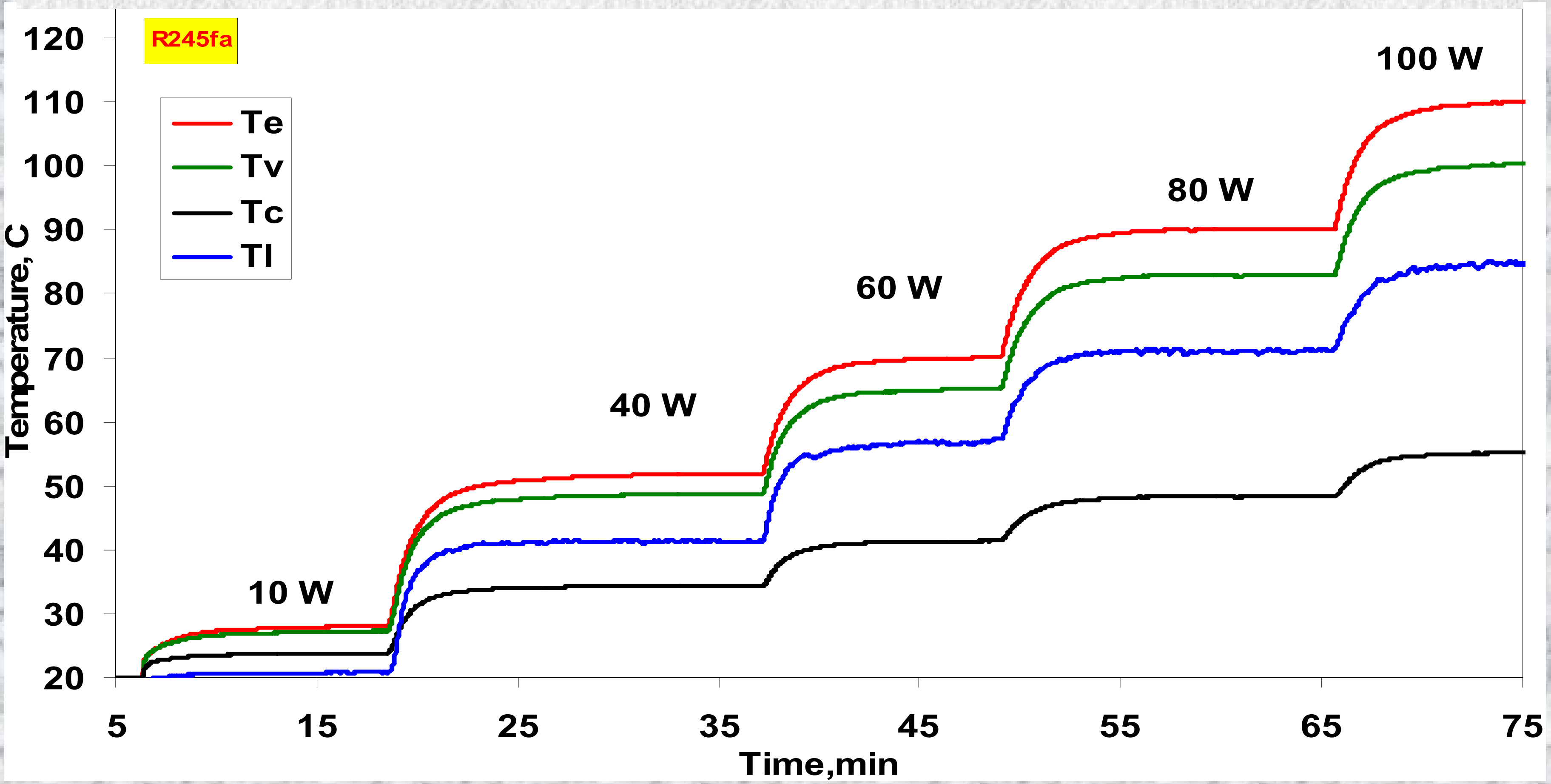
Evaporation inside the wick. Capillary pumping is available from the liquid rivulet at the bottom of the evaporator

# Temperature evolution in LTCE (R245fa) via heat load and distance




*Temperature profile along LTCE as a function of heat load in the evaporator.*
***Working fluid – R245fa***.

# Temperature evolution in LTCE via heat load and time




*Start-up of LTCE thermosyphon, as a function of time; $T_e$, $T_v$, $T_c$ and $T_l$ are the temperatures of evaporator, vapor flow, condenser and liquid respectively.* ***Working fluid – R245fa*****.**

# Conclusions

- The thermal resistance of the LTCE evaporator is close to R = 0.05 - 0.1 K/W. The heat flow density for LTCE (L = 100 mm) is equal $q = 48\ kW/m^2$.
- The LTCE represent a certain advances over state-of-the-art cooling devices in terms of performance, robustness and simplicity. The shape of the LTCE evaporator can be made as cylindrical, or a flat one. The design of LTCE is non expensive and light.
- At a heat load of 100 W, the surface temperature of the LTCE evaporator is 105 °C for R245fa.

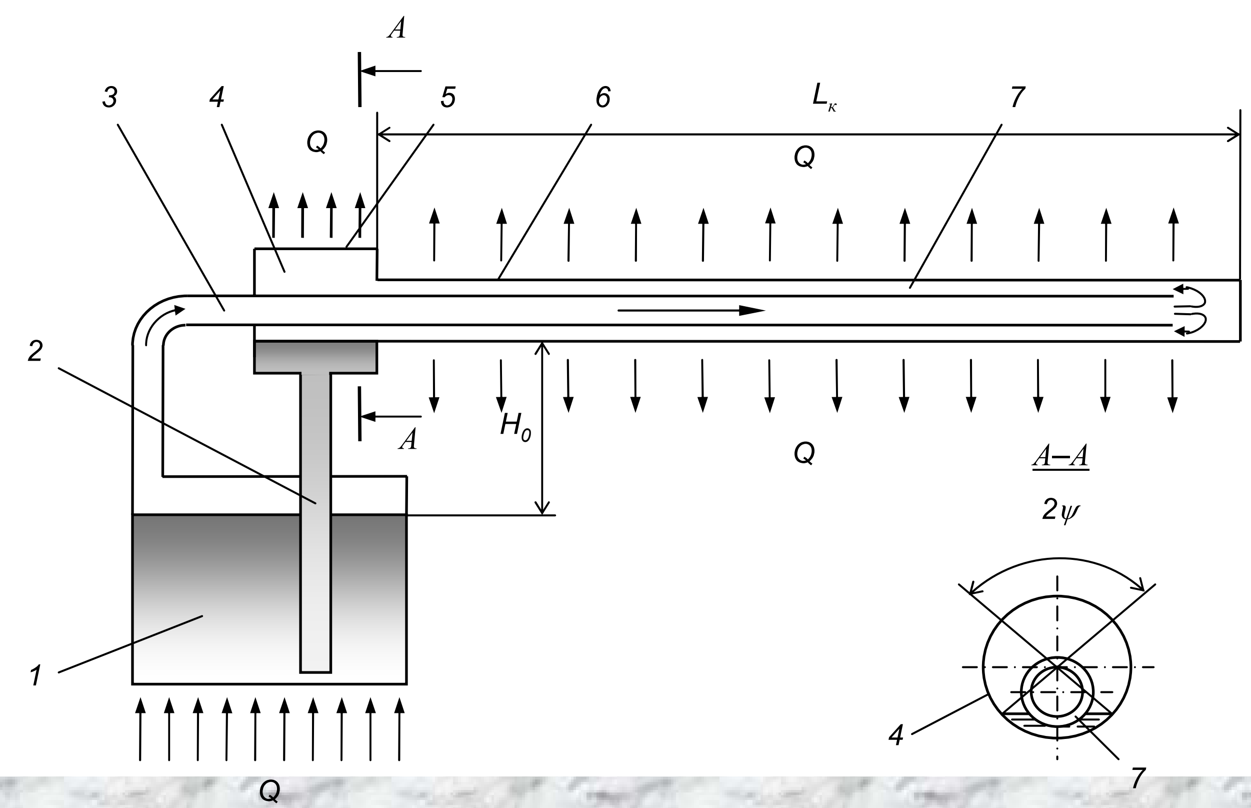
# *Part 3*

- **Vapordynamic thermosyphon with liquid mini heat exchanger (VDT);**
- **Active cooling system of the ANG tank during its charging**

# INTRODUCTION

- Efficiency of the adsorption natural gas (ANG) tanks depends on their possibilities of charging a gas during a short period of time inside porous materials (adsorbents) at a high density and low pressure.
- This work is aimed at ensuring a fast charging of the ANG storage tank using both active (recirculation loop) system and passive (long vapordynamic thermosyphon) thermal management system in the sorbent bed. This approach makes it possible to stimulate gas adsorption and avoid the rise of temperature in the storage tank due to the enthalpy of adsorption.
- An effective charging of a thermally controlled ANG gas storage tank is performed in the 195–350 K temperature range and pressures up to 5 MPa at the stationary filling station.

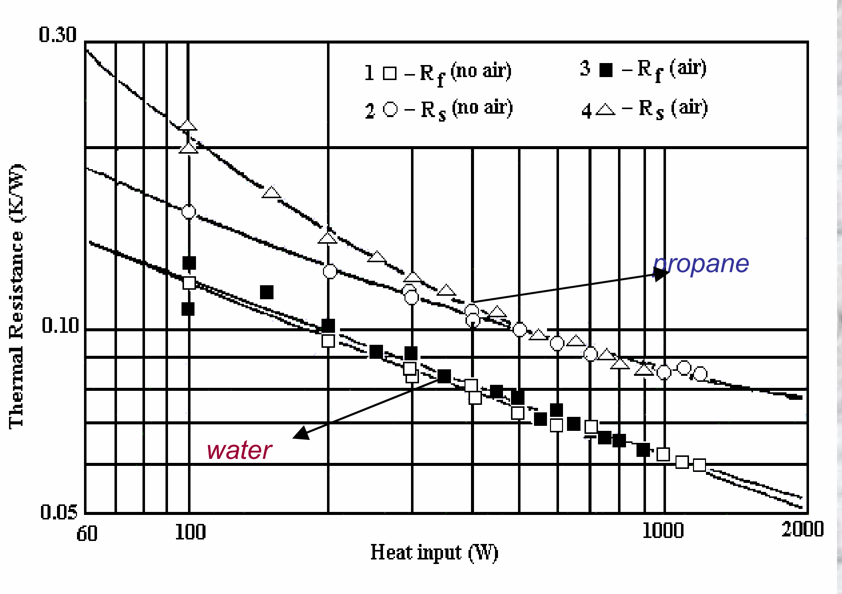
# VAPORDYNAMIC THERMOSYPHON with long horizontal condenser

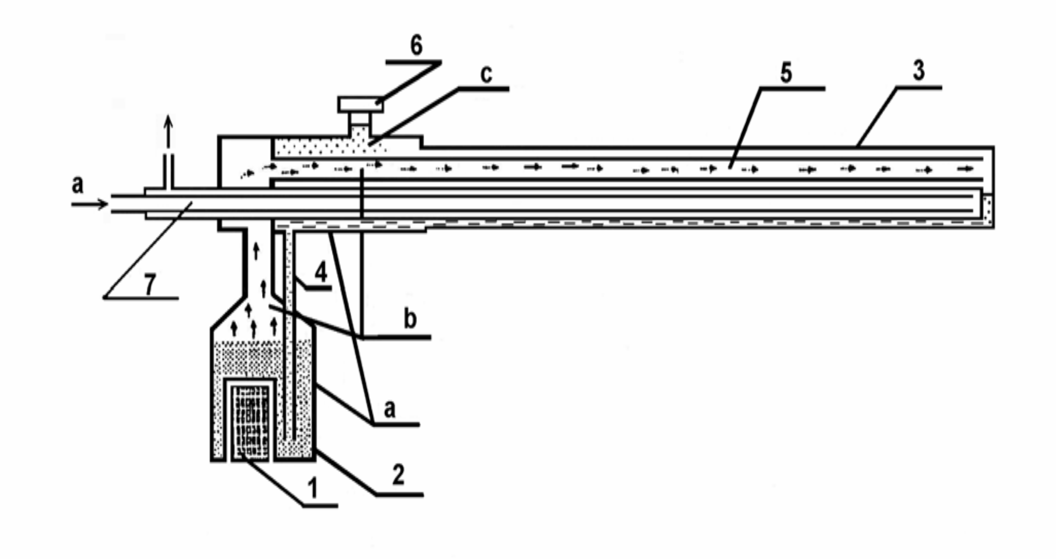



1 – evaporator, 2 – liquid pipe, 3 – vapor pipe, 4 – compensation chamber (NCG trape), 5 – heat sink, 6 – condenser, 7 – annular channel, $H_0$ – hydrostatic pressure drop

Vasiliev, L.L., Morgun V.A., Rabetsky M.I (1985), US Patent No. 4554966, 26.11.1985

# Vapordynamic thermosyphon (VDT) with liquid mini heat exchanger inside it




Thermal resistance R of VDT as a function of heat load (W):
1- water; 2 - propane; 3 - water with air; 4 – propane with an air in the gas trap

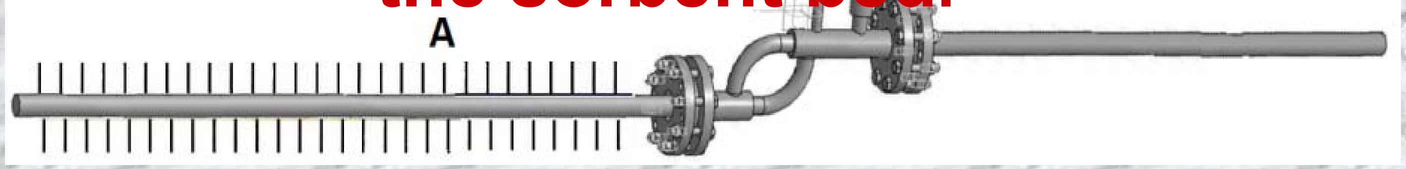
**VDT with liquid mini heat exchanger 7 (tube-in-tube) inside to heat and cool it. a - liquid; b –vapor**

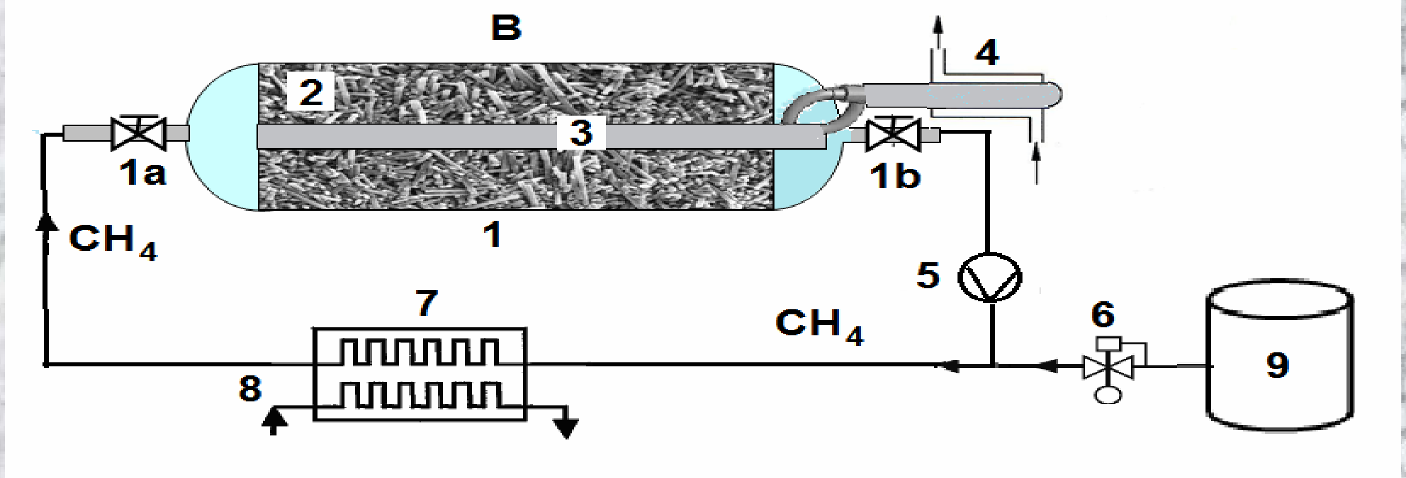
1- cartridge heater; 2 - evaporator; 3 - condenser;
4 - liquid pipe; 5 – vapor pipe ; 6 – NCG trap
7- liquid heat exchanger

**The liquid heat exchanger (efficiency ε = 0.8) is made as a 2 mm SS tube placed inside**

**the annular channel of the VDT condenser.**

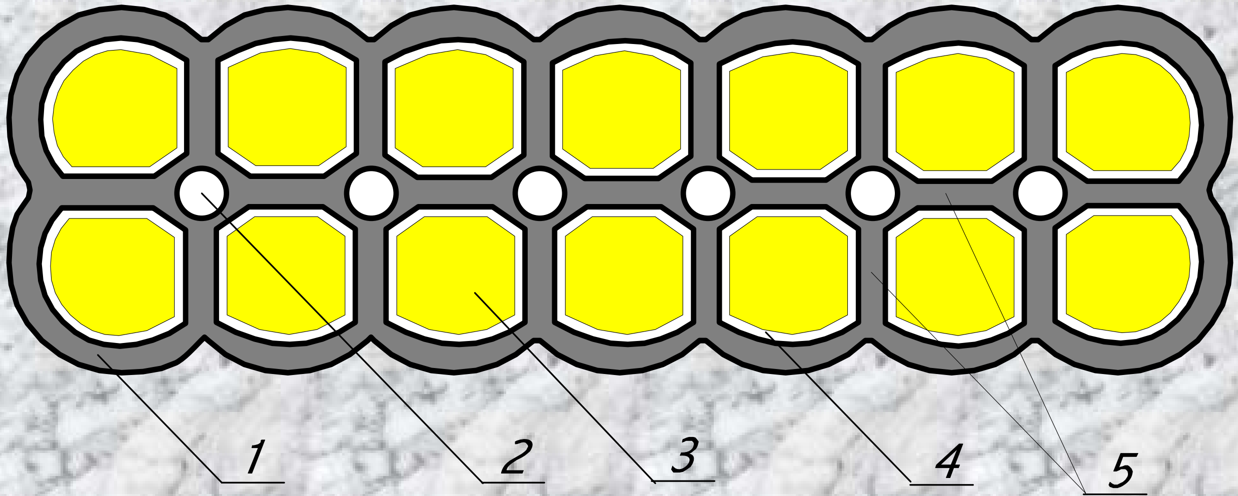
# Active (recirculation loop) and passive (VDT thermosyphon) thermal management system to cool the sorbent bed.



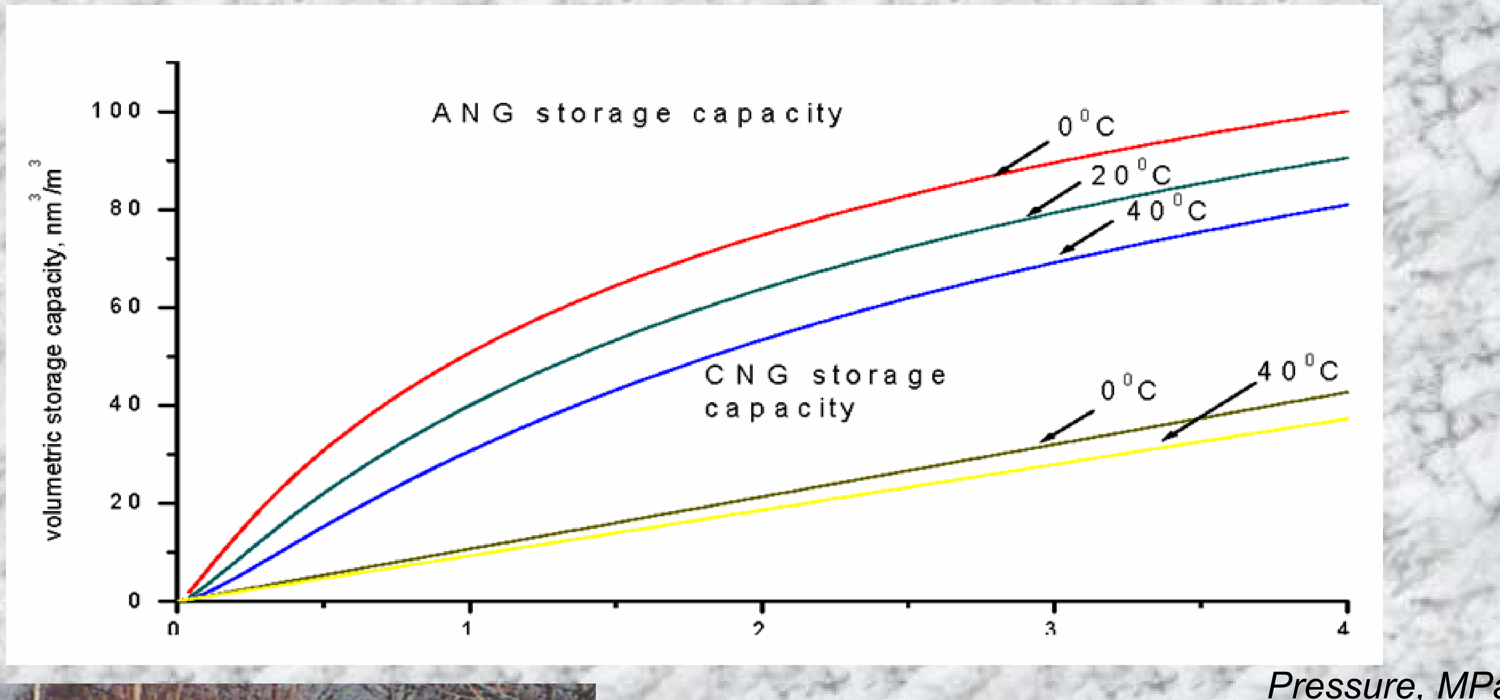

*Thermally controlled device - the long horizontal vapordynamic thermosyphon (A) and scheme of the recirculation charging of a gas tank (B): 1) casing, where 1a and 1b, inlet and outlet tubes with valves; 2) adsorbent; 3) thermosyphon evaporator, 4) liquid heat exchanger; 5) compressor; 6) pressure regulator; 7) external heat exchanger/cooler, 8) cooling device, 9) standard gas tank*

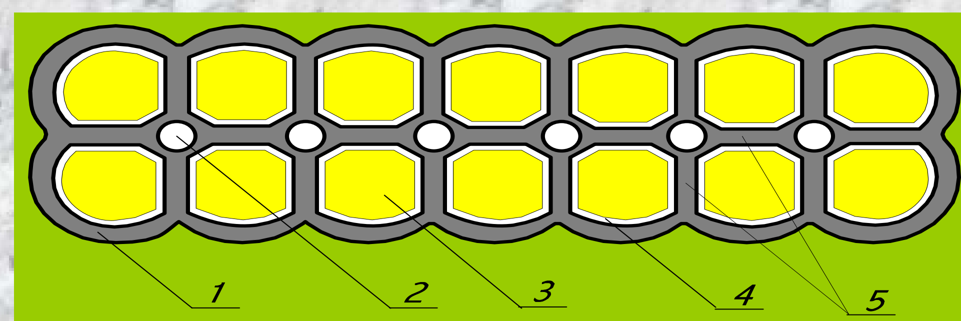
# An advanced 14 cylinder ANG tank with a heat pipe thermal control inside for methane storage and transportation




*1 – gas tank envelope; 2 – heating/cooling elements (heat pipes); 3 – sorbent bed; 4 – gas channels; 5 – metal fins to heat/cool a sorbent bed*

# ANG tank for car engine application




**1 – Al vessel envelope; 2 – heating/cooling elements (heat pipes); 3 – sorbent bed; 4 – gas channels; 5 – metal fins to heat/cool a sorbent bed**

# Conclusions

❖ A physical model of the ANG gas storage tank filling and the corresponding CFD models (with the use of the program complex ANSYS Fluent 14.5) have been developed.

❖Novel vapordynamic (VDT) and loop (LTPE) thermosyphons with annular channels in the long horizontal evaporators were suggested as the convenient passive devices to cool the sorbent bed during the time of the gas storage system charging

❖The innovative technology for controlled charging of a gas storage tank using both passive (thermosyphon) and active (recirculation loop) thermal management systems in sorbent bed has been developed.

❖It is confirmed that the cooling of the adsorbent bed with a finned perforated thermosyphon used in conjunction with the gas recirculation loop makes it possible to control the distribution and level of temperature in the adsorbent bed, and reduces the gas charging time (due to conductive heat transfer and advection of enthalpy) ANG storage tank

❖The results of the work are aimed at creating an alternative system for accumulating gaseous fuels (hydrogen, methane, natural gas) for hybrid cars, electric vehicles, and autonomous consumers.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Sergey_Nik_Melnik