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DYNAMIC DESIGN OF HIGH-PRECISION GAS FLOWMETERS

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Electrohydrodynamic phenomena are effective in various applications of electric fields when controlling volumes, jets and flows of dielectric liquid. Nowadays, one of the most important issues in this area is the implementation of gas saving technologies as well as incensement of their efficiency. It is possible to raise the accuracy of current flowmeters of variable pressure drop on narrowing devices (ND) (which occupy around 70-80 % of the whole world market) by applying innovative compensatory flowmeters with electrohydrodynamic (EH) pressure compensation. At the same time negative inverse connection covers all the signal conversion chain, which makes it possible to exclude an error of each link inside the conversion chain after ND. This article describes the stages of development of an innovative electrohydrodynamic pressure compensation gas flowmeters with electrohydrodynamic inverters (EHI-2F) by using dynamic design and computer methods. They are competitive on the market in terms of accuracy, speed and sensitivity to pressure drop on the ND.

Keywords: gas flowmeters, accuracy, compensation charts, pressure compensation, electrohydrodynamic inverters, dynamic design.

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ДИНАМИЧЕСКОЕ КОНСТРУИРОВАНИЕ ВЫСОКОТОЧНЫХ РАСХОДОМЕРОВ ГАЗА

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Электрогидродинамические явления эффективны в различных приложениях электрических полей при управлении объёмами, струями и потоками диэлектрических жидкостей. Повысить точность наиболее распространенных в мире расходомеров переменного перепада давлений можно в разработанных принципиально новых компенсационных расходомерах с электрогидродинамической (ЭГД) компенсацией по давлению с использованием электрогидродинамических обратных преобразователей с двухфазным диэлектриком – ЭГОП-2Ф. При этом отрицательной обратной связью охватывается вся прямая цепь преобразования сигналов после сужающего устройства (СУ), что позволяет исключить погрешность всех звеньев после СУ расходомера. В статье рассмотрены (с использованием методов динамического конструирования и применением электро-вычислительных машин) этапы разработки инновационных компенсационных по давлению ЭГД расходомеров газа с ЭГОП-2Ф, конкурентоспособных на рынке по показателям точности, быстродействия и чувствительности к перепаду давлений на СУ.

Ключевые слова: расходомеры газа, точность, компенсационные схемы, компенсация по давлению, электрогидродинамические обратные преобразователи, динамическое конструирование.

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Introduction

Papers [1–17, 20, 21] show effective use of electrohydrodynamic phenomena in various applications of electric fields when controlling volumes, jets and flows of dielectric fields.

Nowadays, one of the most important issues in this area is the implementation of gas saving technologies as well as incensement of their efficiency [1, 18, 19]. It is possible to raise the accuracy of current flowmeters of variable pressure drop on narrowing devices (ND) (which have around 70-80 % of the whole worldwide market) by applying innovative compensatory flowmeters with electrohydrodynamic (EH) [1, 2, 20] pressure compensation. At the same time negative inverse connection covers all the signal conversion chain, which makes it possible to exclude an error of each link inside the conversion chain after ND.

The fact is that at the moment, there are compensating flowmeters of variable pressure differential developed and implemented, in which the error of the “displacement-electrical signal” conversion (displacement compensation schemes) and the “force-displacement” conversion (force compensation schemes) is eliminated, while the “pressure-force” conversion remains not covered by the reverse compensation connection. The principles of pressure compensation are described in [22, pp. 13–17], and the principles of force compensation are described in [23, pp. 28–42]. The principle of pressure compensation, that is, as mentioned earlier, the coverage of the entire signal transformation chain by compensatory respond, has not yet been implemented and studied.

This article describes the stages of development of fundamentally new electrohydrodynamic pressure compensation gas flowmeters with electrohydrodynamic inverters (EHI-2F) by using dynamic design (design of the controlled equipment and selection parameters of the control system to ensure the required dynamic indicators) and computer methods [7, 12]. They are competitive on the market in terms of accuracy, speed and sensitivity to pressure drop on the ND.

Further we will consider only the signal conversion chain after the narrowing device of the electrohydrodynamic gas flowmeter in more detail. Fig. 1 shows the following symbols:

W_1 (s) is the transfer function of the link “differential pressure change on the narrowing device (ND) and on the the EH inventer with a two-phase dielectric (EHI-2F) – movement of the working dielectric fluid between the coverings of the capacitive undercompensation sensor (CUS)”

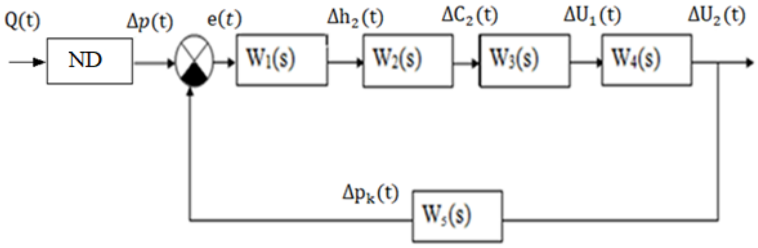

Fig. 1. Structural diagram of the compensation electrohydrodynamic flowmeter with EHI-2F (electrohydrodynamic inverter-2F)

$$W_1(s)=\frac{\Delta h2(s)}{e(s)}=\frac{k_1}{T_1^2 s^2+2\varepsilon T_1 s+1}; \tag{1}$$

$W_2(s)$ is the transfer function of the dynamic element "movement of the working fluid between the coverings of the capacitive undercompensation sensor – change in the capacitance of the capacitive undercompensation sensor"

$$W_2(s)=\frac{\Delta C_2(s)}{\Delta h_2(s)}=k_2; \tag{2}$$

$W_3(s)$ is the transfer function of the element "change in capacitance-voltage at the output of CUS (capacitive undercompensation sensor)"

$$W_3(s)=\frac{\Delta U_1(s)}{\Delta C_2(s)}=\frac{k_3}{s}; \tag{3}$$

$W_4(s)$ is the transfer function of a high voltage amplifier

$$W_4(s)=\frac{\Delta U_2(s)}{\Delta U_1(s)}=\frac{k_4}{T_4 s+1}; \tag{4}$$

$W_5(s)$ is the transfer function of the element "voltage on the electrodes of an EHI – pressure in a fluid at the output of an EHI"

$$W_5(s)=\frac{\Delta p_k(s)}{\Delta U_2(s)}=k_5, \tag{5}$$

here, k_i and T_j are the transfer coefficients and time constants of the corresponding dynamic elements.

Selection of design parameters of the electrohydrodynamic gas flowmeter using dynamic design and computer methods

Further increase in the accuracy and speed of compensatory EH flowmeters can be achieved by selecting transfer coefficients and time constants of elements within the framework of the dynamic formation technology [12], but with a stable compesation scheme.

Let us demonstrate this by the example of choosing the parameters of the element "differential pressure change on the narrowing device (ND) and on the the EH inventer with a two-phase dielectric (EHI-2F) – movement of the working dielectric fluid between the coverings of the capacitive undercompensation sensor (CUS)".

Determination of stability boundaries of the electrohydrodynamic compensation system in the plane of unknown parameters $T_1^2 - k_1$

We find the stability region of the compensation circuit in the plane of the variables of these parameters and the characteristic equation of the closed compensation circuit of the transducer of pressure difference on the control system into an electrical signal as the sum of the numerator and denominator of the transfer function of the open compensation system:

$$\Delta(s) = T_1^2 T_4 s^4 + \left(T_2 T_4 + T_1^2\right)s^3 + \left(T_4 + T_2\right)s^2 + s + k_1 k_2 k_3 k_4 k_5 = 0. \tag{6}$$

Taking into account [1], we have the initial data: $k_1 - ?, T_1^2 - ?, T_2 = 0{,}154\ \text{s}; k_2 = 801{,}6 \cdot 10^{-12} \frac{\varphi}{\text{m}};$ $k_3 = 0{,}2 \cdot 10^{12} \frac{\text{V}}{\varphi}; k_4 = 10^3; T_4 = 1 \cdot 10^{-3}\text{s}; k_5 = 4 \cdot 10^{-9} \frac{\text{Pa}}{\text{V}}.$

Denoting the variable $T_1^2 = \tau$, and another unknown parameter $k_1 = \mu$, we find the boundary of the oscillatory stability of the compensation converter of the pressure difference on the CS into an electric signal (see Fig. 1) in the plane of the unknown parameters of the flowmeter.

At the same time, we focus on the Mikhailov frequency stability criterion, assuming at the same time that the pressure difference on the control system of the flowmeter changes according to a harmonic law with a circular frequency ω. The choice of this stability criterion was based on the fact that it is applicable to both open and closed control systems. At the same time, the Mikhailov stability criterion does not limit the order of the differential equation describing the control system. To highlight the region of stability of the flowmeter, we are interested in the boundary of the oscillatory stability, when the Mikhailov hodograph, the real and imaginary part of the characteristic complex of the compensation scheme (Fig. 1) built in the coordinates, passes through the origin (Fig. 2).

The characteristic complex of the closed compensation circuit (Fig. 1) is obtained from the characteristic equation (1) by replacing the Laplace operator s with $j\omega$: $s = j\omega$, where $j = \sqrt{-1}$, ω is the circular frequency of the harmonic input signal of the pressure differential at the ND of the flowmeter.

Then equation (1) can be represented as

$$\tau Q(s) + \mu P(s) - R(s) = 0, \tag{7}$$

where $R(s)$ is a polynomial, in which neither τ nor μ are included.

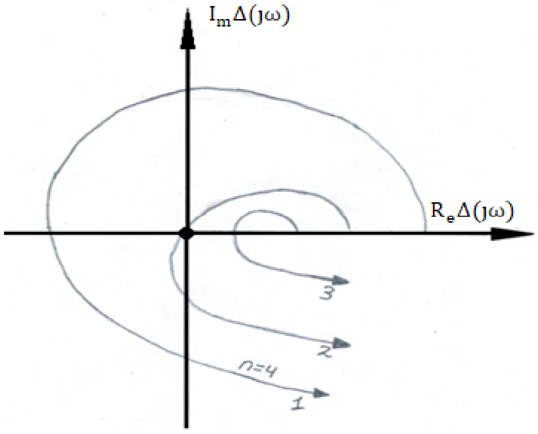

Fig. 2. Possible Nyquist hodographs from different values of unknown parameters T_1^2 and k_1 of the compensation electrohydrodynamic gas flowmeter: stability operation of the flowmeter (1); at the stability boundary (2); unstable operation of the gas flowmeter (3)

From the equations (1), (2) we can find the characteristic complex of a closed system, substituting $s = j\omega$ into the characteristic equation.

To separate the stability region of the compensation system for measuring the pressure difference on the control system (Fig. 1) for two unknown parameters τ and μ, first of all, it is necessary to find the boundary of its stability when the Mikhailov hodograph passes through the origin at some frequency, not changing its smooth spiral shape. Wherein:

$$\begin{cases} R_e\Delta(j\omega)=0 \\ I_m\Delta(j\omega)=0 \end{cases}. \tag{8}$$

Then, taking into account (2), (3) for the oscillation stability boundary, we have:

$$\begin{cases} \tau Q_1(\omega)+\mu P_1(\omega)=R_1(\omega) \\ \tau Q_2(\omega)+\mu P_2(\omega)=R_2(\omega) \end{cases}, \tag{9}$$

where, $Q_1(\omega)$, $P_1(\omega)$, $R_1(\omega)$ are the corresponding polynomials with τ, μ, and the constant term in (2) with even degrees ω, which corresponds to $\mathrm{Re}\Delta(j\omega) = 0$; $Q_2(\omega)$, $P_2(\omega)$, $R_2(\omega)$ are polynomials with uneven degree ω, which corresponds to $\mathrm{Im}\Delta(j\omega) = 0$.

Thus, we have two equations with two variables that are solved for τ and μ using determinants:

$$\tau=\frac{\begin{vmatrix} R_1(\omega) & P_1(\omega) \\ R_2(\omega) & P_2(\omega) \end{vmatrix}}{\begin{vmatrix} Q_1(\omega) & P_1(\omega) \\ Q_2(\omega) & P_2(\omega) \end{vmatrix}}=\frac{R_1(\omega)\cdot P_2(\omega)-P_1(\omega)\cdot R_2(\omega)}{Q_1(\omega)\cdot P_2(\omega)-P_1(\omega)\cdot Q_2(\omega)}=\frac{\Delta_1(\omega)}{\Delta(\omega)}, \tag{10}$$

$$\mu=\frac{\begin{vmatrix} Q_1(\omega) & R_1(\omega) \\ Q_2(\omega) & R_2(\omega) \end{vmatrix}}{\begin{vmatrix} Q_1(\omega) & P_1(\omega) \\ Q_2(\omega) & P_2(\omega) \end{vmatrix}}=\frac{Q_1(\omega)\cdot R_2(\omega)-R_1(\omega)\cdot Q_2(\omega)}{Q_1(\omega)\cdot P_2(\omega)-P_1(\omega)\cdot Q_2(\omega)}=\frac{\Delta_2(\omega)}{\Delta(\omega)}, \tag{11}$$

where

$$\begin{cases} \Delta(\omega)=Q_1(\omega)\cdot P_2(\omega)-P_1(\omega)\cdot Q_2(\omega); \\ \Delta_1(\omega)=R_1(\omega)\cdot P_2(\omega)-P_1(\omega)\cdot R_2(\omega); \\ \Delta_2(\omega)=Q_1(\omega)\cdot R_2(\omega)-R_1(\omega)\cdot Q_2(\omega). \end{cases}$$

Taking into account equation (1) and substituting the numerical values of the parameters, we have:

$$Q_1(\omega)=T_4\omega^4=10^{-3}\omega^4;\ Q_2(\omega)=-\omega^3;\ P_1(\omega)=k_2k_3k_4k_5=64128\cdot 10^{-8};$$

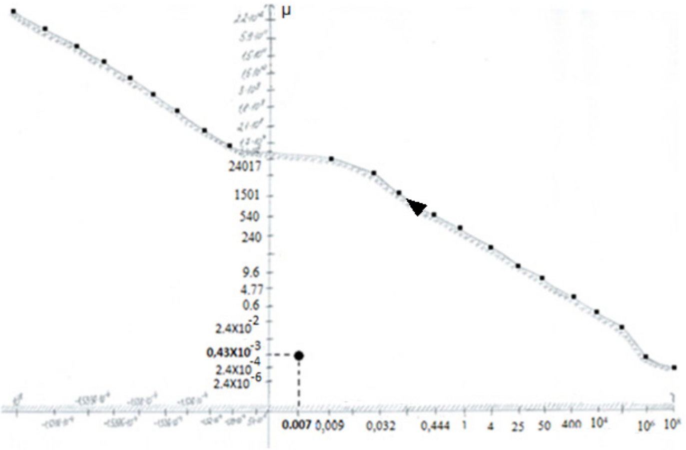

Fig. 3. Selection of unknown parameters from the range of stable operation of electrohydrodynamic flowmeter in the plane of parameters $T_1^2 = \tau, k_1 = \mu$

$$P_2(\omega) = 0;$$

$$R_1(\omega) = (T_4 + T_2)\omega^2 = 155 \cdot 10^{-3}\omega^2;\ R_2(\omega) = T_2 T_4 \omega^3 - \omega = 154 \cdot 10^{-6}\omega^3 - \omega.$$

We use the NAG1 program to calculate the values of τ and μ. We introduce the coefficients of polynomials with degrees ω. We consider values of frequencies of possible flowmeter operation from 10^{-4} to 10^4 1/s. A printout fragment of the PC calculation results to build a D-partition curve is shown in Appendix 1.

On the plane of the parameters τ and μ, we plot the corresponding interconnected points. Herewith frequencies are not indicated on this curve, but only the direction of the frequency increasing is indicated. Moreover, τ is plotted on the abscissa axis, and μ is on the ordinate axis. The geometrical location of these points when ω varies is the oscillatory boundary of the stability of a closed system (Fig. 1). Thus, we obtain the D curve – the plane partitions of the selected parameters τ, μ (Fig. 3).

To know which side the stability region of the system is located in the plane of the parameters τ – μ, we perform the hatching of the D-partition curve. For this, we indicate the direction of frequency increasing ω on the D-partition curve. The hatching is as follows. If one presumably stands on the D-partition curve and moves along it in the direction of frequency increasing ω, and if the main determinant $\Delta(\omega) > 0$ is positive, the curve is dashed with a double hatch to the left, which is the case here. We find special lines that are determined by equating the first and last coefficients of the characteristic equation (1) to zero. They coincide with the coordinates (Fig. 3). The special straight line along the axis does not hatch, since the sign of the determinant does not change at the intersection. The special straight line on the abscissa axis is dashed with a single hatching in the direction of the hatching of the D-partition curve, since there is an asymptotic convergence.

The area limited by shading inward is the area of stable operation of the flowmeter, which is confirmed by further calculations using the NAG2 program. From this area, select a point with coordinates (Fig. 3):

$$k_1 = \mu = 0,43 \cdot 10^{-3};\ T_1^2 = \tau = 0,007\,\text{s}. \tag{12}$$

Selection of design parameters of a gas flowmeter based on the research results that ensure stable operation of the flowmeter

Based on the unknown parameters found in (12), we developed the design of the EHI-2F with capacitive output, which combines module transducer of the differential pressure on the flowmeter control

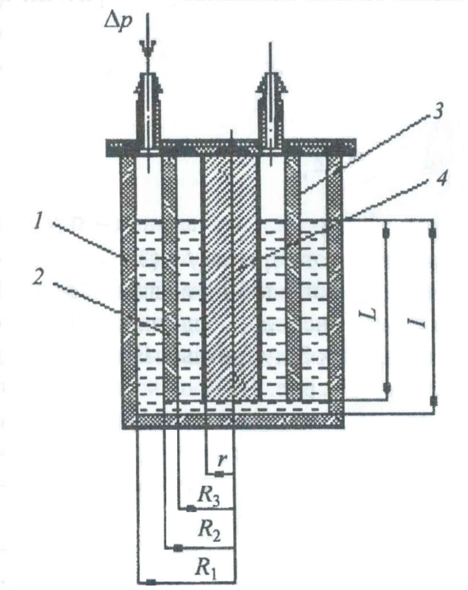

Fig. 4. Construction (based on the research results) of EHI-2F and a capacitive undercompensation sensor of an electrohydrodynamic gas flowmeter

system into the displacement of the working fluid (transformer oil), the EHI-2F as well as CUS electrodes (Fig. 4) in the single formation. Here, 1, 2 are high-voltage electrodes EHI-2F; 3,4 are lining CUS.

The design parameters in Fig. 4 are selected on the basis of (12) taking into account the following conditions [1]:

$$k_1 = \frac{R_1^2 - R_2^2}{pg\left(R_3^2 - r^2\right)}, \tag{13}$$

$$T_1 = \sqrt{\frac{\left(R_3^2 - r^2\right)}{g}}\left[\frac{l_1}{R_1^2 - R_2^2} + \frac{\left(R_1 - r\right)^2}{R_1^2\left(l - l_1\right)} + \frac{l_1}{R_3^2 - r^2}\right]. \tag{14}$$

As a result, the following rational parameters were selected to ensure the competitiveness of the developed innovative compensatory gas flowmeter on the market: $R_1 = 15.75$ mm; $R_2 = 12.85$ mm; $R_3 = 11.9$ mm; $r = 10.95$ mm; $l = 60$ mm; $l_1 = L = 55$ mm.

Conclusion

This article considered the use of compensating flowmeters of variable pressure drop with electrohydrodynamic pressure compensation to improve the accuracy and sensitivity of measuring the flow of transported liquids and gases. In addition, the article discussed the basic construction principles of the electrohydrodynamic compensation using the dynamic design methods and automatic control theory. At the initial stage, the transfer functions of all the links included in the EHI block diagram were defined. The article further identified the transfer functions in an open-loop mode and selected the settings of the two unknown parameters of the inertial link electrohydrodynamic system: transmission coefficient k_1 and time constant T_1^2. In the plane of flowmeter operability boundary, we identified the range of its stable operation.

With the selected design values of the flowmeter parameters, a point with coordinates (0.00043; 0.00725) was selected. This point is included in the stability area of the compensation scheme. This is the novelty and practical significance of the research.

Since in formulas (13, 14) we have interrelated design parameters that can be chosen in various combinations, with the abovementioned design parameters, numerous know-hows that have independent value on the market are provided in the developed innovative compensation gas flowmeter. The introduction of these flowmeters into the existing channels for the transportation of natural fuels will create a competitive advantage for the fuel suppliers by potentially reducing the product cost.

Appendix 1

Printout fragment of the PC calculation results to build a D-partition curve

```
Nagorny A.I.
System order 4
Coefficients of polynomials

     p1            p2            q1            q2            r1            r2
0  6.41E-0004    0.00E+0000    0.00E+0000    0.00E+0000    0.00E+0000    0.00E+0000
1  0.00E+0000    0.00E+0000    0.00E+0000    0.00E+0000    0.00E+0000   -1.00E+0000
2  0.00E+0000    0.00E+0000    0.00E+0000    0.00E+0000    1.55E-0001    0.00E+0000
3  0.00E+0000    0.00E+0000    0.00E+0000   -1.00E+0000    0.00E+0000    1.54E-0004
4  0.00E+0000    0.00E+0000    1.00E-0003    0.00E+0000    0.00E+0000    0.00E+0000


      ω                τ                  μ                  D
   1.0E-0004      1.000000E+0008     2.401447E-0006     6.412800E-0016
   5.0E-0004      1.000000E+0007     2.456843E-0004     3.408876E-0014
   1.0E-0003      1.000000E+0006     4.301442E-0004     1.348264E-0012
   5.0E-0003      4.132412E+0004     6.143256E-0003     5.815066E-0010
   1.0E-0002      1.000000E+0004     2.401345E-0002     2.484800E-0009
   5.0E-0002      4.001632E+0002     6.133251E-0001     4.412800E-0008
   1.0E-0001      5.000371E+0001     4.771442E+0000     2.356800E-0007
   2.5E-0001      2.501130E+0001     9.600130E+0000     6.916217E-0006
   5.0E-0001      3.998246E+0000     6.006021E+0001     8.020811E-0005
   1.0E+0000      9.996460E-0001     2.401930E+0002     6.414724E-0004
   1.5E+0000      4.442312E-0001     5.403989E+0002     2.164753E-0003
   2.0E+0000      2.498210E-0001     9.606787E+0002     5.131010E-0003
   2.5E+0000      1.598332E-0001     1.501034E+0003     1.002120E-0002
   3.0E+0000      1.109497E-0001     2.161466E+0003     1.731629E-0002
   3.5E+0000      8.147399E-0002     2.941977E+0003     2.749724E-0002
   4.0E+0000      6.234288E-0002     3.842569E+0003     4.104500E-0002
   4.5E+0000      4.922652E-0002     4.863245E+0003     5.844054E-0002
   5.0E+0000      3.984440E-0002     6.004008E+0003     8.016481E-0002
   5.5E+0000      3.290265E-0002     7.264861E+0003     1.066988E-0001
   6.0E+0000      2.762285E-0002     8.645809E+0003     1.385234E-0001
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6.5E+0000	2.351391E-0002	1.014685E+0004	1.761196E-0001
7.0E+0000	2.025358E-0002	1.176800E+0004	2.199685E-0001
7.5E+0000	1.762330E-0002	1.350926E+0004	2.705508E-0001
8.0E+0000	1.547061E-0002	1.537063E+0004	3.283477E-0001
8.5E+0000	1.368650E-0002	1.735212E+0004	3.938400E-0001
9.0E+0000	1.219140E-0002	1.945373E+0004	4.675087E-0001
9.5E+0000	1.092610E-0002	2.167547E+0004	5.498348E-0001
1.0E+0001	9.845800E-0003	2.401735E+0004	6.412992E-0001
1.5E+0001	7.021560E-0003	3.521780E+0004	7.316953E-0001

2.6E+0002	-1.392071E-0004	1.733120E+0007	1.127115E+0004
5.1E+0002	-1.501553E-0004	7.870795E+0007	8.506648E+0004
7.6E+0002	-1.522687E-0004	2.188252E+0008	2.815066E+0005
1.0E+0003	-1.530197E-0004	4.948673E+0008	6.607116E+0005
1.3E+0003	-1.533701E-0004	9.865324E+0008	1.282801E+0006
1.5E+0003	-1.535614E-0004	1.796032E+0009	2.207896E+0006
1.8E+0003	-1.536772E-0004	3.048092E+0009	3.496116E+0006
2.0E+0003	-1.537525E-0004	4.889949E+0009	5.207580E+0006
2.3E+0003	-1.538042E-0004	7.491358E+0009	7.402409E+0006
2.5E+0003	-1.538413E-0004	1.104458E+0010	1.014072E+0007
2.8E+0003	-1.538687E-0004	1.576440E+0010	1.348264E+0007
3.0E+0003	-1.538896E-0004	2.188812E+0010	1.748829E+0007
3.3E+0003	-1.539059E-0004	2.967552E+0010	2.221777E+0007
3.5E+0003	-1.539188E-0004	3.940894E+0010	2.773123E+0007
3.8E+0003	-1.539293E-0004	5.139321E+0010	3.408876E+0007
4.0E+0003	-1.539378E-0004	6.595568E+0010	4.135051E+0007
4.3E+0003	-1.539449E-0004	8.344621E+0010	4.957658E+0007
4.5E+0003	-1.539508E-0004	1.042372E+0011	5.882709E+0007
4.8E+0003	-1.539559E-0004	1.287234E+0011	6.916217E+0007
5.0E+0003	-1.539602E-0004	1.573224E+0011	8.064193E+0007
5.3E+0003	-1.539639E-0004	1.904741E+0011	9.332649E+0007
5.5E+0003	-1.539671E-0004	2.286408E+0011	1.072760E+0008
5.8E+0003	-1.539699E-0004	2.723075E+0011	1.225505E+0008
6.0E+0003	-1.539723E-0004	3.219817E+0011	1.392102E+0008
6.3E+0003	-1.539745E-0004	3.781933E+0011	1.573152E+0008
6.5E+0003	-1.539764E-0004	4.414948E+0011	1.769256E+0008
6.8E+0003	-1.539781E-0004	5.124612E+0011	1.981015E+0008
7.0E+0003	-1.539797E-0004	5.916901E+0011	2.209031E+0008
7.3E+0003	-1.539810E-0004	6.798014E+0011	2.453904E+0008
7.5E+0003	-1.539823E-0004	7.774377E+0011	2.716236E+0008
7.8E+0003	-1.539834E-0004	8.852640E+0011	2.996628E+0008

8.0E+0003	-1.539844E-0004	1.003968E+0012	3.295682E+0008
8.3E+0003	-1.539853E-0004	1.134259E+0012	3.613998E+0008
8.5E+0003	-1.539862E-0004	1.276871E+0012	3.952177E+0008
8.8E+0003	-1.539870E-0004	1.432559E+0012	4.310821E+0008
9.0E+0003	-1.539877E-0004	1.602099E+0012	4.690532E+0008
9.3E+0003	-1.539883E-0004	1.786292E+0012	5.091909E+0008
9.5E+0003	-1.539889E-0004	1.985961E+0012	5.515556E+0008
9.8E+0003	-1.539895E-0004	2.201951E+0012	5.962071E+0008

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