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A Method to Measure Dust Production and Deposition Rates for a Ventilated Airspace without Recirculation Systems

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ABSTRACT

A method was developed to estimate dust production and deposition rates for a ventilated airspace without a recirculation system under steady-state conditions. The method was derived from a dust mass balance equation and parameter estimation method. The measured variables required for using the method were the dust concentrations and ventilation rates of the ventilated space. The outputs of the method were dust production and deposition rates. This method actually converted the difficult measurements of dust production and deposition rates into the simple measurements of dust concentrations and ventilation rates. The method was not sensitive to the choice of initial values of parameters and proved to be valid for ventilation rates within the range of 0.083 m^3/s to 0.46 m^3/s.

INTRODUCTION

Measuring dust production and deposition rates is important for both the fundamental physics of and the application of indoor air quality control (Albright 1989; Kusuda 1989; Int-Hout III 1989). This measurement is very difficult to conduct directly in occupied ventilated space such as livestock buildings. Substantial effort has been made and several ways have been tried to determine dust production and deposition rates. Direct measurements of dust deposition rate in occupied livestock buildings were not successful because of random disturbances by pigs at the dust samplers (Barber et al. 1991; Carpenter and Fryer 1990; Zhang et al. 1994). Van Wicklen (1982) measured the dust production rate in a livestock building. He indicated that the measurement involved many uncertainties such as management activities in the building. Qi et al. (1992) measured the "net production rate," which could not differentiate the dust production and deposition rates.

A method was developed to measure dust production and deposition rates under steady-state conditions for livestock buildings (Chen 1996). The method involves measurement of dust concentration vs. filtration efficiency of the recirculation system. An alternative method should be developed if (1) the filtration efficiency of the recirculation system cannot be measured or (2) there is not a recirculation system for the ventilated space.

The objectives of this research were (1) to develop a new technique to estimate dust production and deposition rates for a ventilated airspace without recirculation systems, (2) to conduct the sensitivity analysis of the technique to inputs, and (3) to validate the technique by using the published data.

MATERIALS AND METHOD

Physical Model

For a typical ventilated space without a recirculation system under steady-state conditions, outside air enters the room through air inlets. The outside air is then mixed with the contaminated air in the room. The mixed air is exhausted by ventilation fans. Meanwhile, dust is generated by the animals, fecal materials, and feed within the room. As a result of gravitational settling, Brownian diffusion, and airflow-caused impaction, dust is deposited onto the room surfaces. Under steady-state conditions, a mass balance of dust can be written as

$$m_p = m_e + m_d + m_n - m_s \tag{1}$$

where

m_p = dust production rate, mg/s;

m_e = rate of dust removed by exhaust air, mg/s;

m_d = dust deposition rate, mg/s;

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m_n = rate of dust removed by animal inspiration, mg/s;

m_s = rate of dust brought in by supply air, mg/s.

the variables m_e, m_n, and m_s in Equation 1 can be measured without much difficulty; m_e could be measured by measuring dust concentration and exhaust air rate at the exhaust air outlet, m_n could be measured by measuring dust concentration near animals and inspiration rates of animals, and m_s could be measured by measuring dust concentrations and ventilation rates at the supply air inlet. Difficulty exists in measuring m_p and m_d. If either m_p or m_d is known, the other could be obtained from Equation 1.

Analytical Solution

The mathematical form of the mass balance equation (1) can be further expressed as

$$m_p + Q_s C_a - Q_e C_e - Q_n C_n - m_d = 0 \quad (2)$$

where all variables are defined in "Nomenclature."

For isothermal conditions, volumetric flow rates of supply and exhaust air are equal:

$$Q_s = Q_e . \quad (3)$$

For a well-mixed space, we have

$$C_e = C_n = C . \quad (4)$$

Dust deposition rate can be expressed as

$$m_d = \alpha C \quad (5)$$

where α is the overall dust deposition coefficient units of m^3/s.

α is dependent on deposition surfaces as well as deposition velocity, which is a function of the particle size distribution and the airflow pattern. Research on particle size distribution of swine building dust (Chen et al. 1995) showed that the size distribution of swine building dust did not vary significantly among rooms housing pigs. If the airflow pattern in the room does not appear to change, α may be constant for a given space under a specific operating condition.

Finally, Equation 1 becomes

$$m_p + Q_s C_a - Q_s C - Q_n C - \alpha C = 0 . \quad (6)$$

Solving C from Equation 6, gives

$$C = \frac{m_p + Q_s C_a}{Q_s + Q_n + \alpha} . \quad (7)$$

Equation 7 represents a nonlinear relation between C and α. A nonlinear model does not permit estimation via the solution of a set of simultaneous linear equations (Nash and Smith 1987). Generally, parameters need to be calculated by an iterative computer search procedure. The search procedure generally requires the user to specify "initial guesses" of the parameter values, which are ideally close to the actual values that minimize the sum of squares (Hayter 1996). The application of the nonlinear parameter estimation method requires more computational effort than the sequential estimation procedure used in the work (Kennedy and Neville 1976). However, Equation 7 is an intrinsically linear model that can be transformed into a linear format. Such transformation should be performed whenever it is possible (Hayter 1996). Equation 7 is transformed to a linear model by using a coordinate transformation:

$$\bar{C} = C - C_a . \quad (8)$$

We have

$$\bar{C} = \frac{m_p + Q_s C_a}{Q_s + \alpha + Q_n} - C_a = \frac{m_p - (\alpha + Q_n) C_a}{Q_s + \alpha + Q_n} . \quad (9)$$

By introducing a new variable

$$Y = \frac{1}{\bar{C}} . \quad (10)$$

Then,

$$Y = \frac{Q_n + \alpha}{m_p - (\alpha + Q_n) C_a} + \frac{1}{m_p - (\alpha + Q_n) C_a} Q_s \quad (11)$$

or

$$Y = b_1 + b_2 Q_s \quad (12)$$

where b_1 and b_2 are constants given by

$$b_1 = \frac{Q_n + \alpha}{m_p - (\alpha + Q_n) C_a} \quad (13)$$

and

$$b_2 = \frac{1}{m_p - (\alpha + Q_n) C_a} . \quad (14)$$

The problem has been transformed into the estimation of b_1 and b_2 in the linear Equation 12.

The estimates of m_p and α can be obtained by

$$m_p = \frac{1 + b_1 C_a}{b_2} . \quad (15)$$

$$\alpha = \frac{b_1}{b_2} - Q_n . \quad (16)$$

From Equation 5, the dust deposition rate can be calculated.

Sequential Estimation Method

The sequential estimation procedures refer to continuously updating parameters as new observations are added (Beck and Arnold 1977). Some advantages of the sequential method are that matrix inverses are not necessary and the

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needed computation time can be greatly reduced. No separate method is needed for the solution of a set of simultaneous algebraic equations. By converting a nonlinear problem (such as Equation 7) into a linear problem (such as Equation 12), similar results are obtained with much simpler computation process.

The formulas used in the sequential method are listed as follows:

$$b_{1,i+1} = b_{1,i} + K_{1,i+1}e_{i+1} \quad (17)$$

$$b_{2,i+1} = b_{2,i} + K_{2,i+1}e_{i+1} \quad (18)$$

$$K_{1,i+1} = \frac{A_{1,i+1}}{\Delta_{i+1}} \quad (19)$$

$$K_{2,i+1} = \frac{A_{2,i+1}}{\Delta_{i+1}} \quad (20)$$

$$A_{1,i+1} = X_{i+1,1}P_{11,i} + X_{i+1,2}P_{12,i} \quad (21)$$

$$A_{2,i+1} = X_{i+1,1}P_{21,i} + X_{i+1,2}P_{22,i} \quad (22)$$

$$e_{i+1} = Y_{i+1} - (X_{i+1,1}b_{1,i} + X_{i+1,2}b_{2,i}) \quad (23)$$

$$\Delta_{i+1} = \sigma^2_{i+1} + X_{i+1,1}A_{1,i+1} + X_{i+1,2}A_{2,i+1} \quad (24)$$

$$P_{11,i+1} = P_{11,i} - K_{1,i+1}A_{1,i+1} \quad (25)$$

$$P_{12,i+1} = P_{12,i} - K_{1,i+1}A_{2,i+1} \quad (26)$$

$$P_{21,i+1} = P_{21,i} - K_{2,i+1}A_{1,i+1} \quad (27)$$

$$P_{22,i+1} = P_{22,i} - K_{2,i+1}A_{2,i+1} \quad (28)$$

where

e = difference between the observations and the estimation results,

P_{ij} = covariance of estimators b_1 and b_2,

X_{ij} = matrix for the sensitivity coefficients,

Y_i = observations,

σ^2 = variance,

i = data point, and

j = number of parameters.

A computer program was written based on the above formulas. The convergence criterion can be set by the user of the program. The alternatives for setting the convergence criterion included (1) setting a certain value for e or (2) setting that the parameters did not change significantly for successive iterations. The convergence criterion for trial 1 (see next section) was set to be $e < 2E\text{-}4$, for example.

RESULTS AND DISCUSSION

Gao and Feddes (1993) measured dust concentrations vs. ventilation rates with known dust production rates, and their data can be used to test the parameter estimation method.

Liao and Feddes (1992) developed a lumped-parameter model for describing the behavior of airborne dust in animal housing. Gao and Feddes (1993) carried out an experiment using swine dust to verify this model. Their conclusion was that the predictions of the model compared very favorably with the measured results. Ventilation rate and dust production rate were used as two independent factors. During the experiments, these two factors, each having three levels, were replicated three times in random order. The results of the measurements are listed in Table 1. m_p is the dust production rate measured by the units of particles/s. C_U is the upper level value of dust concentration, C_L is the lower level value of dust concentration, and C is the pooled values of dust concentration. The concentration was measured by the units of particles/m^3.

Gao and Feddes presented the dust data in terms of particle count rather than total dust mass. Rather than convert the particle number data to dust mass data based on some assumptions about particle shape and density, Equation 7 was used as a particle conservation equation. In so doing, particle agglomeration/coagulation and particle aerodynamic segregation,

TABLE 1
Experimental Data Based on Gao and Feddes (1993)

	m_p (10^6 particles/s)	Q_s (m^3/s)	C_U (10^6 particles/m^3)	C_L	C	α (m^3/s)	m_d (10^6 particles/s)
Trial 1	8.9	0.083	66.9	71.0	69.0	0.0459	3.1671
		0.250	28.9	30.5	29.7	0.0497	1.4761
		0.416	18.4	19.4	18.9	0.0549	1.0376
Trial 2	9.2	0.083	69.0	73.4	71.2	0.0462	3.2894
		0.250	29.9	31.5	30.7	0.0497	1.5258
		0.416	19.8	20.0	19.5	0.0558	1.0881
Trial 3	11.0	0.083	83.5	88.7	86.1	0.0447	3.8487
		0.250	36.1	38.1	37.1	0.0465	1.7252
		0.416	23.0	24.3	23.7	0.0481	1.1399

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two potentially important mechanisms for decreasing or increasing the particle count without changing the total mass of dust, were ignored.

The deposition coefficient α was calculated based on Equation 7 with the known production rates in Table 1. The average values of α are 0.0502, 0.0506, and 0.0464 for trials 1, 2, and 3, respectively. The values for C_a and Q_n were assumed to be zero. Input data to the parameter estimation method are the values of C and Q_s, listed in Table 1.

Estimation results are shown in Table 2. Comparisons of the estimated dust production rates with the experimental values show that the agreement between the estimation results and the experimental values was acceptable for all trials. It is interesting that the value of α was so consistent for different ventilation rates. Apparently, increasing the ventilation rate did not change the settling characteristics of the dust. Within the range of ventilation rates used in pig barns, it appears that increasing ventilation rates (and air movement) does not increase the rate of resuspension of dust. However, as the ventilation rate increased, the fraction of dust cleared by deposition decreased because more dust was removed by ventilation air exchange.

Tables 3 and 4 give values of A, Δ, K, and P for trial 1. Each iteration i represents a replication (row) in Table 1. These values are the same for estimating parameters by using data of trials 2 and 3. Therefore, the calculation can be simplified. Table 4 shows that covariance (P) values decreased considerably, indicating that the new measurements substantially reduced the estimate's uncertainty. Initial values used to initiate the program were $b_{1,i} = 0.0$ and $b_{2,i} = 0.0$.

Initial value of covariance matrix P is:

$$P = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} = \begin{bmatrix} 10^5 & 0 \\ 0 & 10^5 \end{bmatrix}$$

Sensitivity matrix X is:

$$X = \begin{bmatrix} X_{11} & X_{21} \\ X_{21} & X_{22} \\ X_{31} & X_{23} \end{bmatrix} = \begin{bmatrix} 1 & 0.083 \\ 1 & 0.25 \\ 1 & 0.416 \end{bmatrix}$$

The sensitivity analysis of the technique was conducted by using data from trial 1. Table 5 shows the parameter estimation results based on different initial values of b_1 and b_2 for trial 1. The agreement between the measured data and the

TABLE 2
Comparison of the Estimated Results with the Experimental Values

		Estimated	Experimental	Relative error %
Trial 1	m_p	8.6680	8.9	--2.61
	α	0.0424	0.0502	−15.54
Trial 2	m_p	8.9444	9.2	−2.78
	α	0.0422	0.0506	−16.60
Trial 3	m_p	10.8896	11.0	−1.0
	α	0.0435	0.0464	--6.25

TABLE 3
Calculation of A, Δ, and K

Iteration, i	A_1	A_2	Δ	K_1	K_2
1	100000	8300	100690	0.99	0.08
2	−1375.6	16585.8	2771.84	−0.5	5.98
3	−2.47	17.87	5.96	−0.42	3

TABLE 4
Calculation of P values

Iteration, i	P_{11}	P_{12}	P_{21}	P_{22}
1	685.17	−8243.13	−8243.13	99315.82
2	2.48	−11.92	−11.92	71.6
3	1.46	−4.5	−4.5	18.02

TABLE 5
Parameter Estimation Results Based on Different Initial Values of b_1 and b_2 for Trial 1

Initial values of b	Iteration, i	e	$b_{1,i}$	$b_{2,i}$
$b_1 = 0.0, b_2 = 0.0$	1	0.0145	0.0144	0.0012
	2	0.019	0.005	0.1148
	3	0.0002	0.0049	0.1153
$b_1 = 0.005, b_2 = 11$	1	−0.9035	−0.8923	10.9255
	2	−1.8054	0.0037	0.1226
	3	−0.0018	0.0044	0.1173
	4	0.0004	0.0048	0.1173
	5	−0.0004	0.005	0.1148
	6	0.0002	0.0049	0.1154
$b_1 = 0.5, b_2 = 0.1$	1	−0.4938	0.0096	0.0593
	2	0.0093	0.005	0.1148
	3	0.0002	0.0049	0.1153
$b_1 = 0.05, b_2 = 0.1$	1	−0.0438	0.0065	0.0964
	2	0.0031	0.005	0.1148
	3	0.0002	0.0049	0.1154
$b_1 = 0.005, b_2 = 1.1$	1	−0.0818	−0.0762	1.0933
	2	−0.1634	0.0048	0.1155
	3	0.0001	0.0049	0.1155
$b_1 = 100.0, b_2 = 100.0$	1	−108.29	−7.5436	91.0739
	2	−15.191	−0.0045	0.1744
	3	−0.0152	0.0019	0.1289
	4	0.0019	0.0038	0.129
	5	-0.0024	0.005	0.1148
	6	0.0002	0.0049	0.1154

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TABLE 6
Effect of Initial Values of *P* on Convergence Speed and Estimation ($b_{1,1}$=0, $b_{2,1}$=0) for Trial 1

	Iteration	*e*	b_1	b_2
P = 10^3	1	0.0145	0.0144	0.0012
	2	0.019	0.0062	0.1072
	3	0.0021	0.0054	0.1133
	4	−0.0003	0.0051	0.1133
	5	0.0003	0.005	0.1147
	6	0.0002	0.0049	0.1153
P = 10^5	1	0.0145	0.0144	0.0012
	2	0.019	0.005	0.1148
	3	0.0002	0.0049	0.1153
P = 10^7	1	0.0145	0.0144	0.0012
	2	0.019	0.005	0.1148
	3	0.0002	0.0049	0.1154

TABLE 7
Effect of Initial Values of *P* on Convergence Speed and Estimation ($b_{1,1}$=100, $b_{2,1}$=100) for Trial 1

	Iteration	*e*	b_1	b_2
P=10^3	1	−108.29	−7.4379	91.0827
	2	−15.299	−0.8703	5.6747
	3	−1.4374	−0.2927	1.4413
	4	0.1876	−0.1066	1.4567
	5	−0.2239	−0.0105	0.2067
	6	−0.0226	−0.0014	0.1401
	7	0.0043	0.0028	0.1405
	8	−0.0043	0.0047	0.1166
	9	−0.0003	0.0048	0.1158
	10	0.0001	0.0049	0.1158
P=10^5	1	−108.29	−7.5436	91.0739
	2	−15.191	−0.0045	0.1744
	3	−0.0152	0.0019	0.1289
	4	0.0019	0.0038	0.129
	5	−0.0024	0.005	0.1148
	6	0.0002	0.0049	0.1154
P=10^7	1	−108.286	−7.5446	91.0738
	2	−15.1902	0.0049	0.1154
	3	0	0.0049	0.1155

fitted values of dust concentrations indicates the goodness of fit of the overall model ($e < 0.0002$). Findings from the sensitivity analysis include: (1) final results of b_1 and b_2 are not significantly affected by the choice of their initial values; (2) a good guess of the initial values for b_1 and b_2 yields fast and accurate estimates; and (3) b_2 is a dominant parameter in this method. If the initial value of b_2 is near the "true" value, the final results and the number of iterations are not affected by the value of b_1. The same conclusions can be drawn for trials 2 and 3 regarding these points.

Tables 6 and 7 show the effect of different initial values of *P* on the number of iterations and the final results. The parameter estimation results are slightly affected when *P* values range from 10^5 to 10^7. The number of iterations is apparently affected by the changes of *P* values. The larger values of *P* lead to fast convergence. Tables 8 and 9 show the effect of different initial values of σ^2 on the number of iterations and the final results. Overall, setting the initial values of *P* to be 10^5 and σ^2 to be unity is allowable by considering both convergence speed and the final results of the sequential estimation method.

It should be noted that in this example, the overall deposition coefficients were almost the same for all three trials, which ensured that ventilation rate could be used as an independent variable to estimate dust production and deposition rates. Changes in the ventilation rate within the range of 0.083 m^3/s to 0.46 m^3/s do not apparently result in changes in the overall deposition coefficient. Ventilation rate at 0.083 m^3/s corresponds to the minimum ventilation rate required for a growing-finishing pig room of floor area 27 m^2 with 55 animals, and ventilation rate at 0.46 m^3/s corresponds to the minimum ventilation required for a growing-finishing pig room of floor area 153 m^2 with 306 animals (Agriculture Canada 1979). Nevertheless, it is likely that a change of ventilation rate may cause a change of airflow pattern, which, in turn, may change the overall deposition coefficient. In that case, after using this method to get production and deposition rates, the validation work on the overall deposition coefficient should be performed. For a ventilation space with a recirculation system, a better alternative would be to adjust the filtration efficiency, which is not expected to change α.

To show credibility of the linear transformation and the sequential method, the results of a nonlinear least squares fitting method (SAS 1994) are also presented in Table 10. The difference between the proposed method and the nonlinear estimation method is less than 3% for both m_p and a.

CONCLUSIONS

Dust production and deposition rates can be measured for an occupied ventilated space without a recirculation system under steady-state and well-mixed conditions by an indirect method. The method was derived from a mass balance equation and parameter estimation technique. It actually converts a difficult measurement of dust production and deposition rates into a simple measurement of dust concentrations vs. ventilation rate.

The method proved to be valid for a ventilated room with ventilation rates of 0.083 m^3/s to 0.46 m^3/s. For cases in which ventilation rates are out of this range, the method should be

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TABLE 8
Effect of Initial Values of σ^2 on Convergence Speed and Estimation for $b_{1,1}$= 0, $b_{2,1}$= 0 for Trial 1

	Iteration	e	b_1	b_2
$\sigma^2 = 10$	1	0.0145	0.0144	0.0012
	2	0.019	0.0062	0.1072
	3	0.0021	0.0054	0.1133
	4	−0.0003	0.0051	0.1133
	5	0.0003	0.005	0.1147
	6	0.0002	0.0049	0.1153
$\sigma^2 = 1.0$	1	0.0145	0.0144	0.0012
	2	0.019	0.005	0.1148
	3	0.0002	0.0049	0.1153
$\sigma^2 = 0.1$	1	0.0145	0.0144	0.0012
	2	0.019	0.005	0.1148
	3	0.0002	0.0049	0.1153

TABLE 9
Effect of Initial Values of σ^2 on Convergence Speed and Estimation ($b_{1,1}$ = 100, $b_{2,1}$ = 100) for Trial 1

	Iteration	e	b_1	b_2
$\sigma^2 = 10.0$	1	−108.286	−7.4379	91.0827
	2	−15.2991	−0.8703	5.6747
	3	−1.4375	−0.2927	1.4413
	4	0.1876	−0.1066	1.4567
	5	−0.2239	−0.0105	0.2067
	6	−0.0226	−0.0014	0.1401
	7	0.1424	0.0018	0.1518
	8	−0.006	0.0043	0.1181
	9	−0.0006	0.0046	0.1164
	10	0.0006	0.0051	0.1133
	11	0.0002	0.005	0.1147
	12	0.0002	0.0049	0.1153
$\sigma^2 = 1.0$	1	−108.29	−7.5436	91.0739
	2	−15.191	−0.0045	0.1744
	3	−0.0152	0.0019	0.1289
	4	0.0019	0.0038	0.129
	5	−0.0024	0.005	0.1148
	6	0.0002	0.0049	0.1154
$\sigma^2 = 0.1$	1	−108.286	−7.5446	91.0738
	2	−15.1902	0.0049	0.1153
	3	0	0.0049	0.1154

TABLE 10
Estimated Dust Production Rate and Overall Deposition Coefficient for Three Trials

	m_p			α		
	Linear	Nonlinear	Difference %	Linear	Nonlinear	Difference %
Trial 1	8.6680	8.6919	0.3	0.0424	0.0429	1.17
Trial 2	8.9444	8.9847	0.45	0.0422	0.0432	2.31
Trial 3	10.8896	10.8879	0.01	0.0435	0.0435	0

used with caution and validation work should be performed to check the overall deposition coefficient.

This method is not sensitive to the choice of the initial values of b_1 and b_2. Any starting values for b_1 and b_2 will be expected to give good results. However, b_2 is a dominant parameter. A good guess of initial value for b_2 will reduce calculation time and yield a fast convergence to final results. The initial values of P and σ^2 do not apparently affect the estimates but affect the number of iterations.

The proposed method will need further validation subject to (1) generality of unsteady-state field conditions and (2) different room configurations with different airflow patterns.

NOMENCLATURE

- b_1, b_2 = parameters
- C = dust concentration, mg/m^3 or particles/m^3
- C_a = dust concentration of outside air, mg/m^3
- C_e = dust concentration of ventilation exhaust air, mg/m^{3}or particles/m^3
- C_L = the lower level value of dust concentration, particles/m^3
- C_n = dust concentration of air inspirated by animals, mg/m^3
- C_s = dust concentration of ventilation supply air, mg/m^3
- C_U = the upper level value of dust concentration, particles/ m^3
- e = the difference between the observations and the estimation results
- m_d = rate of dust deposition, mg/s or particle/s
- m_e = rate of dust removed through exhaust air, mg/s or particle/s
- m_n = rate of dust removed by animal inspiration, mg/s
- m_p = dust production rate, mg/s or particles/s
- m_s = rate of dust brought in through supply air, mg/s
- Q_e = air exchange rate through exhaust air system, m^3/s
- Q_n = air exchange rate inspirated by animals, m^3/s
- Q_s = air exchange rate through air supply system, m^3/s
- P = covariance of estimator
- X = sensitivity coefficient

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Y = observations
α = overall deposition coefficient, m^3/s
σ^2 = variance

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