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Algebraic Calculation Algorithm with Some Assisting Techniques for Petrochemical Pipe Network Simulation

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Abstract: In industry scene, it is complex pipe networks connect various unit equipments together to be a whole system. Similarly, in simulation plant and platform, correct and efficient calculation of pipe networks is the key point to connect each simulation model of independent unit equipment together. But due to the weakness of time-consuming, the traditional methods, which do pipe network calculation by iteration and trial -error method to solve nonlinear equations are no longer available. Borrowing ideas from the circuit theory, using Approximate Linearization and superposition principle, we presented an algebraic pipe network calculation method in this paper. And both Complex Pipe Network Pressure and Flowrate Monitoring Experiment Device, which was designed and manufactured by ourselves, and real running data of Methyl Acrylate production process in some plant were used to verify such method in the last section.

Keywords: chemical processes, simulation, pipe network calculation, superposition principle

1 Introduction

With the rapid development of process simulation technology, simulation models and related products of unit equipments have tended to be more and more mature [1,2].In order to establish system-wide simulation plant and platform, researchers have to find out an effective method to realize the simulation calculation of pipe networks, which join all of the independent unit equipments together in industry scene. Such method should not only present the relationship between pressure and flowrate accurately, but it also could not influence the calculation of other unit equipment models, which means it should be completed within an iteration step of other units or a shorter time.

Pipe network calculation methods used currently can be divided into three categories: conventional method, graph theoretic approach and intelligent method. Hardy Cross method, Pipeline Section Equation method and Node Equation method are three main basic methods of the Conventional category [3,4,5]. Graph theoretic approach mainly includes Solving String Flow Equation method and Solving Branch Attrition Equation method [6,7,8]. In intelligent method, researchers have presented Genetic Algorithm method, Pipe Network Fuzzy approach and method combining Ant Algorithm and Quasi-Newton method, and so on [9,10,11].

To march the requirement of rapid calculating, methods above are not applicable any more. And there are two ways could be chosen: One is promoting the solving speed of above pipe network calculation methods. Such as study on new nonlinear equations calculation method that with less time consuming [4,12,13,14], or improving calculation hardware(such as CUDA technology [15]). Second is thinking about the calculation method itself to propose new rapid method [16,17,18]. This paper focused on the second aspect. Borrowing ideas from the circuit theory, using Approximate Linearization and superposition principle, an algebraic pipe network calculation method that avoids calculating nonlinear equations was presented. And in the last section, both Complex Pipe Network Pressure and Flowrate Monitoring Experiment Device, which was designed and manufactured by ourselves, and real running data of Methyl Acrylate production process in some plant are used to verify such method.

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2 An Algebraic Pipe Network Calculation Method

To calculate pressure and flowrate distribution in pipe networks, relationship between pressure drop and flowrate is the main calculation basis. As we knows, general equation used to calculate pressure drop in pipe is Fanning Equation as shown below [19]:

$$\Delta P_f = \lambda \frac{l}{d} \frac{\rho u_m^2}{2}, \tag{1}$$

$$\lambda = \frac{8\tau}{\rho u_m^2}. \tag{2}$$

where, ΔP_f denotes perssure drop, Pa; λ denotes friction coefficient, dimensionless; l denotes length of pipe, m; d denotes diameter of pipe, m; u_m denotes mean folw velocity, m/s;ρ denotes fluid density, kg/m^3 and τ denotes shearing strength, N/m^2.

Because this paper fours on calculation method of pressure and flowrate distribution, the influence of physical property of fluid, flow status and geometry size of flow course was not analyzed in detail. Establishing the relationship between flowrate and flow velocity by using pipe cross-sectional area, equation (1) could be simplified to:

$$\Delta P_f = Kq^s. \tag{3}$$

Where, K is a scale factor, which is function of pipe friction coefficient, pipe length and diameter, etc. q is flowrate. And the exponent s is a dimensionless number confirmed by physical property of fluid and flow status. Besides, there are two conclusive theorems need to be introduced briefly: For a node in pipe networks, equation (4) can be derived by the law of conservation of mass. Sign of q in this equation should be paid attention. Inflow use positive sign when outflow use negative one.

$$\sum q = 0. \tag{4}$$

And for a mesh in pipe networks, equation(5) can be derived by the law of conservation of energy. Sign of in this equation should also be paid attention. When sets clockwise direction as positive, counter-clockwise direction should be negative.

$$\sum \Delta P_f = 0. \tag{5}$$

These two theorems above correspond to Kirchhoff's current law (KCL) and voltage law (KVL) in circuit theory respectively [20]. Existence of such two congruent relationships establishes the theory basis for the handling method introduced in this paper. In the sections below, algebraic pipe network calculation method presented by this paper will be introduced respectively, direct at different kinds of structures commonly appeared in petrochemical pipe networks.

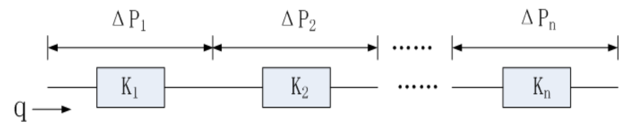

Fig. 1: Pipeline Schematic Diagram of Series Structure

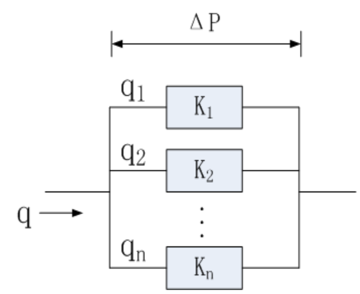

Fig. 2: Pipeline Schematic Diagram of Parallel Structure

2.1 Series Structure

Figure 1 is a schematic diagram of series structure pipeline with n sections. Pressure drops on each section are expressed as ΔP_1-ΔP_n. And scale factors are expressed as K_1-K_n. According to the law of conservation of mass, flowrate through every section are equal and equal to the total flowrate q.

According to the law of conservation of energy, total pressure drop ΔP_f is the sum of pressure drop of all sections. Then substituting equation(3), function between pressure drop and flowrate for series structure can be achieved(equation(7)). And K_{eq} is equivalent scale factor.

$$\Delta P_f = \Delta P_1 + \Delta P_2 + \ldots + \Delta P_n, \tag{6}$$

$$\begin{aligned} \Delta P_f &= K_1 q^s + K_2 q^s + \ldots + K_n q^s \\ &= (K_1 + K_2 + \ldots + K_n) q^s \\ &= K_{eq} q^s, \end{aligned} \tag{7}$$

$$K_{eq} \underline{\underline{def}} \frac{\Delta p}{q^s} = K_1 + K_2 + \ldots + K_n = \sum K_i. \tag{8}$$

2.2 Parallel Structure

Figure 2 is a schematic diagram of parallel structure with n sections. Scale factors are expressed as K_1-K_n. The total flowrate is q. And flowrates of each section are q_1-q_n. According to the law of conservation of energy, pressure drop on each section is equal(expressed as ΔP).

According to the law of conservation of mass, total flowrate q equals to the sum of flowrates of each section. equation(9), which is achieved by substituting equation(3), is the function between pressure drop and flowrate for parallel structure. And K_{eq} is equivalent scale factor.

$$q = q_1 + q_2 + ... + q_n = (\frac{\Delta p}{K_1})^{\frac{1}{s}} + (\frac{\Delta p}{K_2})^{\frac{1}{s}} + ... + (\frac{\Delta p}{K_n})^{\frac{1}{s}} = (\frac{1}{K_1^{\frac{1}{s}}} + \frac{1}{K_2^{\frac{1}{s}}} + ... + \frac{1}{K_n^{\frac{1}{s}}})\Delta p^{\frac{1}{s}}, \quad (9)$$

$$K_{eg} \underline{\underline{def}} \frac{1}{(\frac{1}{K_1^{\frac{1}{s}}} + \frac{1}{K_2^{\frac{1}{s}}} + ... + \frac{1}{K_n^{\frac{1}{s}}})^s} = \frac{1}{(\sum \frac{1}{K_i^{\frac{1}{s}}})^s}. \quad (10)$$

2.3 Structure With Multiple Entrances or Exits

Pipe networks with multiple entrances or exits could also be always found out in petrochemical industry. How to deal with such complex pipe structures? As we know, superposition principle is used in circuit calculation to deal with linear circuit with multiple voltage sources or current sources [20]. However, people who understand superposition principle knows that such theorem could only be used in linear system. But the functional relationship between pressure drop and flowrate is nonlinear (as shown in equation(3)), so it has to be linearized at first. In this paper, Approximate Linearization method was used to handle such nonlinear functional relationship. Here, Approximate Linearization will be introduced briefly at first. Suppose there is a nonlinear functional relationship $y = f(x)$. And $A(x_0, y_0)$ is a working point, so $y_0 = f(x_0)$ could be achieved. Then make a tangent at point A, and the tangent function could be educed as equation(11). Then the above nonlinear function $y = f(x)$ is changed to linear one [21].

$$y = f(x_0) + \frac{df(x)}{dx}|_{x=x_0}(x - x_0). \quad (11)$$

After dealing with the pressure flowrate equation (equation(3)) by the Approximate Linearization, new pressure flowrate equation like can be obtained. However, due to the existence of the constant term, system described by such equation is still not linear. And superposition principle still could not be used. Actually, systems described by are called incrementally linear systems [22]. It could be equivalent to a linear system and a zero input response. And such decomposability has been detailedly proved before [23]. To the linear aspect of the incrementally linear system, superposition principle can be used directly. And after the treatment for the linear aspect by superposition principle, response of the whole system could be obtained by adding the zero input response to homologous linear aspect. Superposition principle suitable for pipe network could be described as following: After the functional relationship between pipe network pressure and flowrate is linearized, the response (pressure and flowrate) at any point in pipe network equals the algebraic sum of the responses caused by each independent pressure source and traffic source acting alone. So-called independent pressure source means pressure difference between an entrance and an exit of pipe network. And independent traffic source means an entrance keeps constant flowrate to input fluid. Besides, following points should be paid attention when using such superposition principle. a).To ascertain the contribution of each individual source, all of the other sources must be set to zero firstly. Replacing all other independent pressure sources with a short circuit; replacing all other independent traffic sources with an ”open circuit”;b).When ascertains the contribution of each individual source, reference direction of pressure drop and flowrate can be defined same with the original direction. When summarizes contribution of each individual source, + and - of pressure drop and flowrate should be paid attention;c).Structure with one entrance and multiple exits (1&n) or multiple entrances and one exit (n&1) corresponds to n independent pressure or traffic sources combined action. Structure with multiple entrances and multiple exits (m&n) corresponds to $m \times n$ pressure or traffic sources combined action.

3 Working Point Estimate Method for Structure with Multiple Entrances or Multiple Exits

The most important part in application of Approximate Linearization is accurate estimation of the working point. Correct estimation of the working point directly relates to the accuracy of the final calculation result. In pipe network calculation problem, working point estimation means estimates flowrate in the pipeline at the moment. In the following sections, working point estimation methods for 1&n or n&1 structure and m&n structure will be introduced respectively in detail.

3.1 1&n(n&1) Structure

Figure 3 is a simplified schematic diagram of 1&n pipe network. In simulation calculation, pressure on boundary point (contact points with other unit experiments or utilities system) is always deemed to be known already. As a result, p_t, $p_{1\cdot 1}$, $p_{1\cdot 2}$, ... $p_{m\cdot nm}$ are known already in figure 3.

In order to estimate flowrate in every part of pipeline, pipe network shown in figure 3 should be simplified at first. If $p_{1\cdot 1}$, $p_{1\cdot 2}$, ... $p_{1\cdot n1}$ are equal to each other, the pipeline marked with p_1 can be simplified based on series or parallel relationship. However, in most situation, $p_{1\cdot 1}$, $p_{1\cdot 2}$, ... $p_{1\cdot n1}$ are not equal. In this paper, average method is used to assume these branch pipes amalgamate together

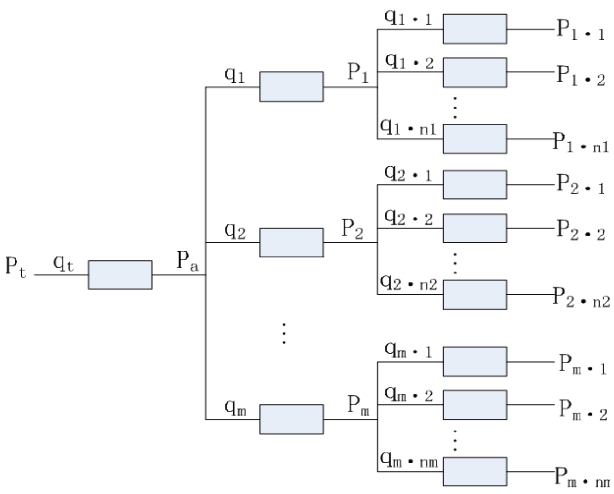

Fig. 3: Simplified Schematic Diagram of 1&n Structure

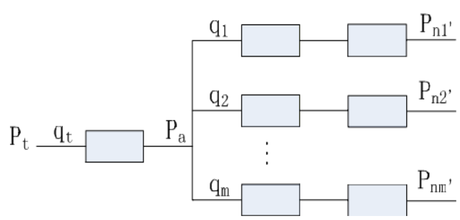

Fig. 4: First Step of Simplification for Pipe Network in Figure 3

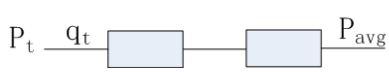

Fig. 5: Second Step of Simplification for Pipe Network in Figure 3

and pressure at the amalgamating point equals to such average value. It is clear that the former situation is the special case of the latter and can be covered by the latter. After the above treatments, pipe network in figure 3 is simplified as shown in figure 4. where,

$$\begin{cases} p_{n1'} = \frac{p_{1\cdot 1}+p_{1\cdot 2}+\ldots+p_{1\cdot n1}}{n1} \\ p_{n2'} = \frac{p_{2\cdot 1}+p_{2\cdot 2}+\ldots+p_{2\cdot n2}}{n2} \\ \ldots \\ p_{nm'} = \frac{p_{m\cdot 1}+p_{m\cdot 2}+\ldots+p_{m\cdot nm}}{nm} \end{cases}. \quad (12)$$

One more step in the same way, structure shown in figure5 will be obtained.

where,

$$\begin{cases} p_{avg1} = \frac{p_{1\cdot 1}+p_{1\cdot 2}+\ldots+p_{1\cdot n1}}{n1} \\ p_{avg2} = \frac{p_{2\cdot 1}+p_{2\cdot 2}+\ldots+p_{2\cdot n2}}{n2} \\ \ldots \\ p_{avgm} = \frac{p_{m\cdot 1}+p_{m\cdot 2}+\ldots+p_{m\cdot nm}}{nm} \\ p_{avg} = \frac{p_{avg1}+p_{avg2}+\ldots+p_{avgm}}{m} \end{cases}. \quad (13)$$

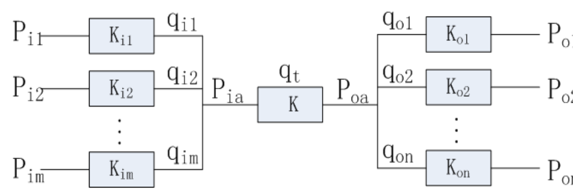

Fig. 6: Simplified Schematic Diagram of m&n Structure

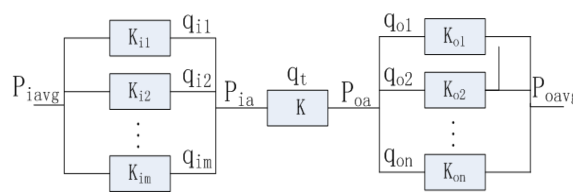

Fig. 7: Simplification of m&n Structure Pipe Network

Then, p_t, p_{avg} and equation (3) can be used to calculate estimation value of total flowrate q_t. Estimation value of p_a in figure 4 can be then calculated by using p_t, q_t and equation (3). In the same way, estimation values of q_1 and all other flowrates can be calculated against the above simplification process. Then working points of all pipes are estimated.

For n&1 structure, structure is same as 1&n structure, so the same estimation method is totally applicative.

3.2 m&n Structure

It is an m&n structure complex pipe network shown in figure 6. As mentioned above, boundary points (p_{i1}-$p_{im}p_{o1}$-p_{on}) are always deemed to be known already. Same as the way to deal with 1&n (n&1) structure, average values of pressure at entrances and exits are calculated respectively at first. Then the above structure can be simplified as shown in figure 7.

Where,

$$\begin{cases} p_{iavg} = \frac{p_{i1}+p_{i2}+\ldots+p_{im}}{m} \\ p_{oavg} = \frac{p_{o1}+p_{o2}+\ldots+p_{on}}{n} \end{cases}. \quad (14)$$

Based on p_{iavg} and p_{oavg} , estimation value of the total flowrate q_t now can be calculated by using series and parallel relationship. Then estimation value of p_{ia} and p_{oa} can be obtained by equation (3). Then combining with the known boundary value (p_{i1}-p_{im}, p_{o1}-p_{on}), estimation value of all parts of the above m&n structure pipe network can be calculated.

4 Experimental Verification

To verify the feasibility and accuracy of the above algebraic calculation method, the Complex Pipe Network

Pressure and Flowrate Monitoring Experiment Device was designed and manufactured by us. And we also collected some real running data of a Methyl Acrylate production process in some plant. In this section, verification will be proceeded based on such two kinds of data. Calculation methods for series and parallel structure are proved adequately in theory. However, structure with multiple entrances or exits has to be verified due to the use of Approximate Linearization and superposition principle. In this section, calculation process for the most common pipe network with one entrance and two exits was taken as an example to make such work.

To proceed pipe network calculation, the exact form of equation (3) has to be confirmed at first. In this paper, Hazen-Williams equation (as shown below) that is always used in pipe network calculation is adopted [24].

$$\Delta p_f = \frac{10.67\rho g l}{C^{1.852} D^{4.87}} q^{1.852}. \qquad (15)$$

Then, ”s” in equation (3) is equal to 1.852. Moreover, Hazen-Williams roughness coefficient C, fluid density ρ, pipe diameter D and pipe length l in equation (15) confirm the scale factor K in equation (3) together. During the verification process, to avoid bringing in extra error form these parameters, running data of experiment and plant is firstly used to calculate the scale factor K of each part of pipe networks by using equation (3). Then, the achieved K can be used in pipe network calculation process.

4.1 Verification Based on Experiment Data

Photo of the Complex Pipe Network Pressure and Flowrate Monitoring Experiment Device is shown in figure 8. The main body is branch and merger structure pipe network that is common in the industrial field. This experimental facility is constructed by stainless steel pipes. Eight pressure measuring and transmitting devices, six flowrate measuring and transmitting devices and four automatic control valves are installed. And all of the signals are collected and recorded by SIEMENS distributed control system PCS7.

Use the above experiment device to do pressure and flowrate monitoring experiment to one entrance and two exits structure part and randomly chose ten sets of data to fill in table 1 below. Calculate the average values of this ten sets of data and compare with the calculation results by the algebraic pipe network calculation method introduced in this paper. Calculate error and percentage error, and fill them into table 1. Table 1 shows that percentage error aimed to the three parts of the one entrance and two exits structure are respectively 0.3%, 0.39% and 0.54%. All of the calculation results are less than 1%, and calculation accuracy is very perfect.

Fig. 8: Photo of the Complex Pipe Network Pressure and Flowrate Monitoring Experiment Device

4.2 Verification Based on Plant Data

In this section, based on some real running data of a Methyl Acrylate production process in some plant, the algebraic pipe network calculation method presented in this paper will be verified. As shown in figure 9, it is a simplified drawing of some equipments and pipe networks in Methyl Acrylate production process. Verification aimed at the branch pipeline that start at the outlet pipe of the centrifugal pump (P-307) and divide into two lines into the top of Methyl Acrylate treating column (T-307) and product storage tank (V-307). Same as the former section, real running data in plant and calculation results obtained by the algebraic pipe network calculation method presented in this paper were both filled in table 2. Error and percentage error were also calculated and filled in. As table 2 shown, percentage error of centrifugal pump outlet pipeline, Methyl Acrylate treating column return pipeline and product storage tank inlet pipeline are respectively 0.372%, 0.014% and 0.013%. Same as the former section, all of the calculation results are less than 1%. Such verification give a further proof that accuracy of the algebraic pipe network calculation method presented in this paper is very ideal.

5 Conclusion

In petrochemical simulation, correct and efficient calculation of pipe networks is the key point to connect simulation models of independent unit equipments together to establish more realistic, system-wide simulation plant and platform that could be defined freely and flexibly by users. Borrowing ideas from the circuit theory, and using Approximate Linearization and superposition principle, this paper presented an algebraic calculation method that avoids calculating nonlinear equations. And in the last section, both Complex Pipe

Table 1: Experiment Data and Calculation Results of One Entrance and Two Exits Structure Pipe Network

	$P_I(\times 10^5 Pa)$	$P_{O1}(\times 10^5 Pa)$	$P_{O2}(\times 10^5 Pa)$	$q_I(m^3/h)$	$q_{O1}(m^3/h)$	$q_{O2}(m^3/h)$
Experiment Value	0.202541	-0.050925	-0.024305	20.4620456	10.3856411	9.83407974
	0.197911	-0.050925	-0.024305	20.3535423	10.5755233	10.1831007
	0.197911	-0.050925	-0.024305	20.4204540	10.3910665	9.99683570
	0.201383	-0.055554	-0.020833	20.6012935	10.5809488	9.87386417
	0.197911	-0.050925	-0.021990	20.2613143	10.5700979	10.1089563
	0.197911	-0.050925	-0.024305	20.4168357	10.5212717	10.0727882
	0.197911	-0.052082	-0.024305	20.2830143	10.4724445	9.86843872
	0.202541	-0.053239	-0.021990	20.4439621	10.4579772	9.88833141
	0.197911	-0.049767	-0.020833	20.3571586	10.4887199	9.94981670
	0.201383	-0.053239	-0.018518	20.3155651	10.5827570	9.91184043
Average Value	0.199532	-0.051850	-0.022569	20.3915185	10.5026448	9.96880521
Calculation Value	0.199532	-0.051850	-0.022569	20.4526609	10.4614437	9.91531638
Error	—	—	—	0.06114239	0.04120107	0.05348883
Percentage Error	—	—	—	0.2998423%	0.3922924%	0.5365621%

Table 2: Plant Data and Calculation Results of Some Equipments and Pipe Networks in Methyl Acrylate Production process

	$PP(\times 10^6 Pa)$	$PT(\times 10^6 Pa)$	$PV(\times 10^6 Pa)$	$qP(kg/h)$	$qT(kg/h)$	$qV(kg/h)$
Plant Value	0.31	0.0399966	0.010896	3000	1000	2000
Calculation Value	0.31	0.0399966	0.010896	2988.830035	1000.143292	2000.257737
Error	—	—	—	11.1699652	0.1432921	0.2577367
Percentage Error	—	—	—	0.3723322%	0.0143292%	0.0128868%

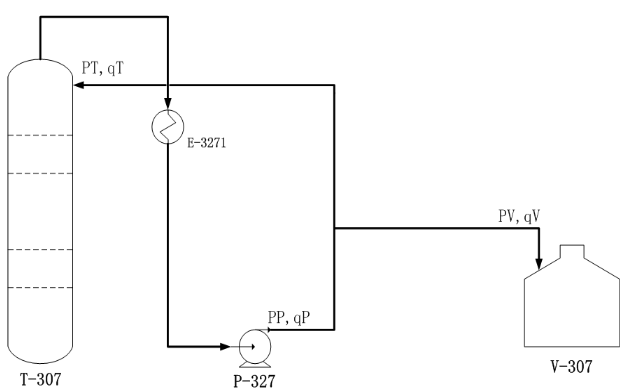

Fig. 9: Simplified Drawing of Some Equipments and Pipe Networks in Methyl Acrylate Production Process

Network Pressure and Flowrate Monitoring Experiment Device and real running data of Methyl Acrylate production process in some plant are used to verify such method. The verification results show that the calculation error of above method is within 1%. The accuracy is perfect. Besides, there is only algebraic calculus but no time-consuming iteration or trial-error steps in the whole calculation process. So, the calculation speed is greatly improved. Further research works aimed at some steps of the introduced calculation method in this paper could be proceeded in future. First, the accuracy of the calculation result may be more outstanding by using method of weighted mean, which is based on fluid property, fluid flow condition and the geometry of the pipe size and shape, to replace the common averaging method used in this paper. Second, Approximate Linearization was used in this paper. Such method is a kind of simple, partial linearization method, which is seriously dependent on the accuracy of working point estimation. Further work could think about adopting some global, more accurate linearization method [21,25] to obtain some more ideal conclusion.

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