Urban Sewage Delivery Heat Transfer System (1):

Flow Resistance and Energy Analysis[1]

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Abstract: The thimble delivery heat-transfer (TDHT) system is one of the primary modes to utilize the energy of urban sewage. Given the schematic diagram of TDHT system, introducing the definition of equivalent fouling roughness height, and using the Niklaus semi-rational resistance coefficient formula in rough region, the calculation methods of the sewage flow resistance are explained. Through the resistance contrastive analysis of sewage and pure mediate water, the results indicate that the mediate water sub-system is the primary design point of the TDHT system. The economical ratio of flux and velocity is determined by optimization analysis of investment and operating cost in the technical feasible range. The paper will provide reference for pipe design and pump selection of urban sewage cool or heat source applied delivery heat transfer methods.

Key words: urban sewage; delivery heat transfer; flow resistance; ratio of flux; ratio of velocity.

1. INTRODUCTION

With the development of the society and the improvement of the quality of life, people have put forward new requests for the living environment that is people who live in North need air conditioning in summer and people who live in South need heating in winter. In the traditional design of the HVAC, heating system usually selects small boiler or urban heating network and air-conditioning system usually selects water chiller or monomer air-conditioning unit. When a construction needs both air conditioning and heating, if adopting two series of main engines and air terminal devices, the owner can not afford the original investment or the cost of operation and maintenance. In recent years, with the further reinforcing structural energy saving policy and the execution of the statute, the heat load per unit area in winter has reduced in North while heat load in South is small essentially, which makes the heating with low temperature come true in countrywide area. Actually, heat pump engineering technology can achieve heating in winter (average temperature between 40~45℃, which belongs to low temperature heating), air conditioning in summer and hot water service in all year, which is an economical, reliable, handy, comfortable system of HVAC. The execution precondition of the heat pump engineering is that there must be appropriate low order cool and heat source. Comparing with air, earth, groundwater, urban sewage has much advantage such as high thermal capacity, large heat transfer coefficient, without intake and recharging well, also it has suitable temperature both in winter and summer [1.2]. But urban sewage has lots of contaminants and solutes, if there is no simple and economical filtration, it is much easy to plug the heat exchanger and the pipe-line equipments [3.4]. In order to save room of machine, traditional heat exchangers usually adopt compact form, so they were usually plugged by sewage. But in actual project, there is a long distance between sewage sewer and construction. Whether it can exchange heat by the delivery area of this

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distance, basing on the elicitation of this, we put forward TDHT system [5] (Thimble Delivery Heat Transfer system). It neither occupies machine room, nor plugs the heat exchanger. The schematic diagram of TDHT system is shown by Fig.1. Because the inner pipe space is smoother than the annular pipe space, urban sewage flows inside while the mediate water flows in the annular pipe. There are parallel-flow and reverse-flow for different direction of the sewage and the mediate water. In an actual project and design of the HDHT system, due to the long pine-line, the questions as following are inevitable: how to determine reasonable pipe diameter, sewage pump, and circulate flow resistance; which is better between the parallel-flow and reverse-flow; whose heat-exchanging efficiency is bigger. The deep researches on the flow resistance, the efficiency of the exchange heat, the economical feasibility of the TDHT system have been done. Basing on the definition of equivalent fouling roughness height and the Niklaus semi-rational resistance coefficient formula in rough region, the thesis introduces the calculation methods of the sewage flow resistance, analyses energy consumption of sewage and mediate water, and determines the economical ratio of flux and velocity of the TDHT system by economical optimization.

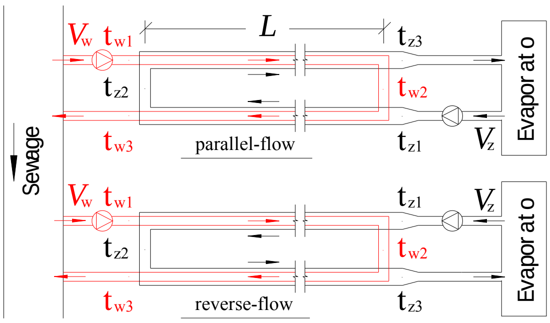

Fig.1 Schematic diagram of TDHT system

2. SEWAGE FLOW RESISTANCE FORMULA

The pipe diameter of the leading urban sewage pipe is usually big, and the velocity of the flow usually designs beyond 1.2m/s [6 7], so in the using of the heat energy, whether it is fed or exchanged, the sewage is always in the turbulent roughness. In this state, the thickness of the gummy bottom is much smaller than the thickness of the protuberant roughness, the roughness protuberance has entered into turbulent core region and destroyed completely the laminar sub layer, so the velocity and the viscosity have less influence on the turbulent degree of the flow and the viscous layer, the flow resistance is independent of Re, the coefficient of the following resistance λ is just the function of the relative roughness thickness k_s/d. It is shown by the search that the sewage flows perennially on the definite velocity, it will form steady fouling on the pipe wall, the roughness thickness of the pipe material does not work longer, so the equivalent roughness thickness of the fouling is put forward, which will be used for the calculation of the flow resistance of the sewage. The balanceable thickness of the fouling is relative to the velocity and the pipe diameter [8], but the roughness thickness of the fouling is relative to the velocity, water quality, exterior peculiarity and so on. In the actual engineering, these properties of the sewage are fixity or comparability, so the roughness thickness of the fouling changes very little. The experimental mensuration and the engineering data have shown that the roughness thickness of the fouling (k_s) is equal to 2mm. It can be brought into the Niklaus semi-rational resistance coefficient formula in rough region [9]:

$$\frac{1}{\sqrt{\lambda}} = \lg\frac{3.7d}{k_s} \qquad (1)$$

By the numeric calculation and the simplification, the power function form, can be obtained, which is used in the engineering easily. It is

$$\lambda_w = \frac{0.0235}{d^{0.30}} \qquad (2)$$

The result of (2) is slight bigger than that of (1), but the errors are within 3%. The results of both are shown in the Fig.2. If the calculation of the sewage flow adopts the *Chezy-Manning* function, similarly, by the numeric calculation and the simplification, the roughness thickness of the fouling $k_s = 2mm$ is equivalent to the roughness coefficient n=0.0014, the result of (2) is slight smaller, but also within 3%. So it is rational that we use the (2) to calculate the flow resistance of the sewage. If the roughness thickness

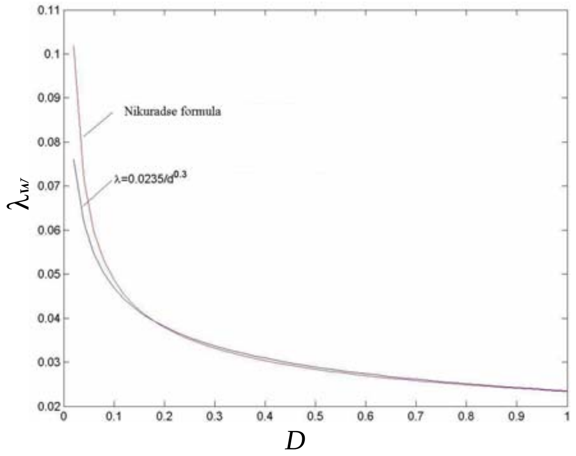

Fig.2 Turbulent resistance coefficient of sewage

of the mediate water pipe is $k_s^{'} = 0.5mm$, the flow resistance of the sewage is about tribal of the mediate water.

This thesis analyses the resistance by the conception of the specific resistance. Specific resistance is

$$a = \frac{8\lambda}{g\pi^2 d^5} \qquad (3)$$

The specific resistance of the sewage is

$$a_w = \frac{0.001944}{d^{5.30}} \qquad (4)$$

by the (4), the calculation table of the different pipe diameter is calculated, which is shown in the table 1. If the length of the single-pass thimble is l, the flow resistance of the sewage is

$$H_w = 2a_w l V_w^2 \qquad (5)$$

Tab.1 Turbulent specific resistance of sewage in pipe（Flow unit: m^3/s）

Diameter（mm）	Specific Resistance（s^2/m^6）	Diameter（mm）	Specific Resistance（s^2/m^6）	Diameter（mm）	Specific Resistance（s^2/m^6）
10	77392033.96	125	118.87	400	0.249907
15	9024280.53	150	45.23	450	0.133866
20	1964433.28	175	19.98	500	0.076587
25	602024.57	200	9.8455	600	0.029140
32	162705.18	225	5.2739	700	0.012873
40	49862.99	250	3.0173	800	0.006343
50	15281.12	275	1.820677	900	0.003398
70	2568.48	300	1.148031	1000	0.001944
80	1265.67	325	0.751129		
100	387.88	350	0.507149		

3. RESISTANCE CONTRAST ANALYSIS

The mediate water pipe will appear incrustations after a period of time, so the calculation of the mediate water flow resistance adopts the Шевлев function which is appropriative to the flow resistance calculation of the old steel pipe and the old cast iron pipe. It is

$$\lambda_z = \frac{0.021}{d^{0.30}} \quad (u > 1.2m/s) \qquad (6)$$

Defined the ratio of flow resistance of mediate water and sewage is $Hr = H_z / H_w$, the ratio of the flux is $Cr = V_w / V_z$,and the ratio of velocity is $Ur = u_z / u_w$, supposed the inside and outside diameter of the inner pipe is d_1, the diameter of the outer pipe is d_2, then

$$d_2 = d_1\sqrt{1+\frac{1}{CrUr}} \tag{7}$$

Mediate water flows along the annular pipe, the equivalent diameter is

$$d_{ze} = d_2 - d_1 = \left(\sqrt{1+\frac{1}{CrUr}} - 1\right)d_1 \tag{8}$$

The specific resistance of the mediate water can be obtained by deduction:

$$a_z = \frac{0.001737}{\left(d_2 - d_1\right)^{3.30}\left(d_2 + d_1\right)^2} \tag{9}$$

Introduced formula (9) into the function of the resistance; the ratio of the flow resistance of mediate water and sewage is got as

$$Hr = 0.8935Cr^{-2}\left(\sqrt{1+\frac{1}{CrUr}} - 1\right)^{-3.30}\left(\sqrt{1+\frac{1}{CrUr}} + 1\right)^{-2} \tag{10}$$

It is obvious that the ratio of the resistance between the mediate water and the sewage lies on the ratio of the flux and the ratio of the velocity. The connection of them is shown in the Fig.3. It is easy to see that although the resistance coefficient of mediate water is smaller than that of sewage, the flow resistance of mediate water is about several times more than that of sewage. The reason is at the same current area, the equivalent diameter of media water is so small. For example, when $Cr = 1.0$, $Ur = 1.0$, the resistance of mediate water is above 95 times more than that of sewage. It is absolutely unallowed on the engineering. So in the engineering design of the heat feeding by the thimble, the emphases and the difficulty of the pipe design and the water pump saving energy should not be the sewage system but the mediate water system. The (10) indicates that the ratio of the flow resistance between mediate water and sewage is just the function of Cr and Ur , then how to confirm the ratio of flux and the velocity of TDTH system is very important. By the mathematic analysis, when Cr and Ur decrease, Hr also decreases strictly. But in the actual engineering, Cr and Ur impossibly decrease to 0 indefinitely. The thesis confirms the systemic technical feasible range of the Cr and Ur basing on the following three points:

(1) When Cr decreases, the flux of mediate water increases, which not only induces that the flux of the mediate water is too large to choose water pump, but also induces that the diameter of the outer pipe is too big to choose, increasing the difficulty of the construction and the systemic first investment. Generally speaking, $Cr \geq 0.4 \sim 0.5$ is feasible, that is the flux of mediate water is 2~2.5 times smaller than that of sewage. When Cr increases, the flow resistance of mediate water increases largely, and the exchange heat efficiency of the system will decrease greatly, so $Cr \leq 1.0$ is better.

(2) When Ur decreases, the velocity of the mediate water decreases, which will not only increase the diameter of the outer pipe and the investment, but also decrease the diathermanous coefficient of the system. Economical velocity of mediate water system is about $1.0m/s$, if Ur is too small, the velocity of sewage will be too big, so $Ur \geq 0.33 \sim 0.4$ is feasible, the velocity of sewage is 2.5~3 times smaller than that of mediate water.

(3) Under the natural condition, the flow resistance of the sewage is about $20m$, considering the pump head of mediate water and the reduction of the function energy consumption, $Hr \leq 5$ is acceptable.

By the numeric analysis and the Fig.3, basing on $Hr \leq 5$, $Cr \geq 0.4 \sim 0.5$, $Ur \leq 0.72 \sim 0.81$ is obtained; basing on $Hr \leq 5$, $Ur \geq 0.33 \sim 0.4$, $Cr \leq 1.0$ is obtained. The ratio of the flux and velocity in the systemic technical feasible range is $0.4 \sim 0.5 \leq Cr \leq 1.0$, $0.33 \sim 0.4 \leq Ur \leq 0.72 \sim 0.81$. (If improving requirement, $Hr \leq 3$, the technical feasible range is $0.4 \sim 0.5 \leq Cr \leq 1.0$, $0.33 \sim 0.4 \leq Ur \leq 0.64 \sim 0.71$.)

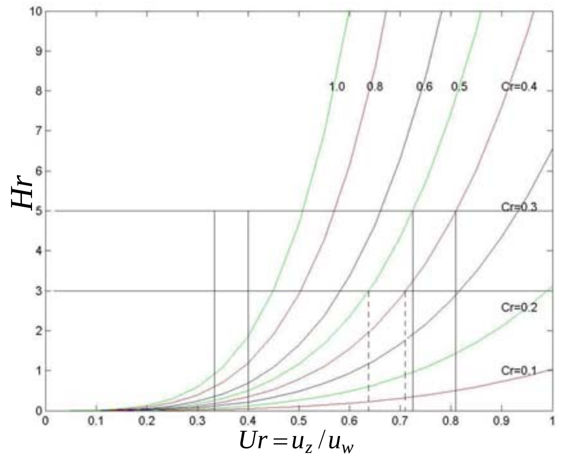

Fig.3 Resistance contrast analysis of TDHTS

4. ECONOMICAL FLUX AND VELOCITY RATIO

In actual engineering, the sewage flux V_w, the sewage velocity u_w, the inner pipe diameter d_1, the single-pass thimble length l and so on, are confined by the cooling and heating load of the building, heat-exchanging areas, no-blockage by contaminant deposition, and their numerical value is relative fixed, changes very little, so the energy consumption and the investment of the sewage system cannot change basically. The total pump power of sewage and mediate water in the TDTH system is:

$$P_c = \eta^{-1} \rho g V_w H_w \left(1 + \frac{Hr}{Cr}\right) \qquad (11)$$

The (11) indicates that the overall pump energy consumption of the system is the function of the Cr and Ur, when decreasing the velocity of mediate water and increasing the flux of the mediate water moderately (when $Cr \cdot Ur \geq 0.017754$, P_c is the monotone function of the Cr, so it is easy to meet), it will reduce the overall pump energy consumption largely. But the (8) indicates that it is cost on the increasing the diameter of the outer pipe, that is the first investment of the pipe material, construction and so on. So how to confirm the flux and velocity of mediate water is an economical optimization question of the investment and the operation. The (8) also indicates that it is the same influencing degree for the investment by the ratio of the velocity Ur and the ratio of the flux Cr, but the (11) indicates that the ratio of the velocity is much larger than the ratio of the flux for the influencing degree of the systemic overall energy consumption. Because about 85% of the thermal resistance of the sewage exchanging system centralizes on the side of sewage, it is a small influence for the heat exchange coefficient to decrease the velocity of mediate water[10 11], but it is a big influence for the heat exchange efficiency to decrease the flux of mediate water, so decreasing the velocity of mediate water is the main means for the double-pass thimble system to control the investment and the energy consumption.

The investment or the cost of the system contains equipment material expenditure, depreciation expenditure, investment interest rate and so on [12]. Equipment material expenditure converts by the quantities of the pipe material consumption (which contains construction and the pump expenditure), calculated by the method of the fixed number of year average, so the investment of the sewage system is

$$I_w = 2\pi d_1 L \delta \rho_s p_s \left(1 + N\alpha_z + (1+\alpha_L)^N\right) \qquad (12)$$

Here: δ -the thickness of the pipe wall; ρ_s -the density of the steel; p_s -the unit price of the steel; N -the fixed number of year; α_z -the average rate of the depreciation; α_L -the rate of the investment. So the total investment of the TDTH system is:

$$I_c = I_w \left(1 + \sqrt{1 + \frac{1}{CrUr}}\right) \qquad (13)$$

The sewage pump power of the TDTH system is:

$$P_w = 2\eta^{-1} \rho g a_w L V_w^3 \qquad (14)$$

The total expenditure function of the sewage pump in the depreciation period is:

$$F_w = N P_w T \varphi p_e \qquad (15)$$

Here: T -the number of the used hours; φ -the load coefficient that is the ratio of the average load and the designed load; p_e -the average electrovalence. So the total expenditure function of the TDTH system is:

$$F_c = F_w\left(1+\frac{Hr}{Cr}\right) \qquad (16)$$

Defined the ratio of investment and operating cost, it is $\sigma = I_w / F_w$. So the total expense function including investment and operating cost in the whole life of the system is:

$$M_c = F_w\left(1+\frac{Hr}{Cr}+\sigma+\sigma\sqrt{1+\frac{1}{CrUr}}\right) \qquad (17)$$

The dualistic optimization in the technical feasible range of Cr and Ur is done, then the economical ratio of the flux and velocity is confirmed. Taking an engineering in Harbin for example, the thickness of the pipe material is $\delta = 6mm$, the price of the pipe material is $p_s = 6000\ yuan/t$, the average rate of the yearly depreciation is $\alpha_z = 10\%$, the average rate of the investment is $\alpha_L = 0.05\%$, the number of heating days is 180 days, the number of the air-conditioning days is 60 days, the water pump functions is 16 hours per day, the load coefficient is $\varphi = 0.641$, the water pump efficiency is $\eta = 0.9$, the velocity of the sewage is $u_w = 2.5m/s$, the average electrovalence is $p_e = 0.8\ yuan/kWh$, the depreciation fixed number of year is $N = 20$ years, so the ratio of the systemic investment and the overall function expenditure is $\sigma = I_w/F_w \approx 0.822$. Let $Mr = M_C / F_W$, the economical ratio of flux and velocity are shown in the Fig.4. The two lines of $\partial Mr/\partial Ur = 0$ and $\partial Mr/\partial Cr = 0$ cut the whole area into three parts. In area I, $\partial Mr/\partial Cr < 0$, $\partial Mr/\partial Ur < 0$. In area □, $\partial Mr/\partial Cr < 0$, $\partial Mr/\partial Ur > 0$. In area □, $\partial Mr/\partial Cr > 0$, $\partial Mr/\partial Ur > 0$. Generally speaking, the optimization point in the technical feasible range will locate at the point of the intersection among vertical line of the Ur floor level, horizontal line of the Cr upper limit and the line of the $\partial Mr/\partial Cr = 0$. (If the point of the intersection is in area □, the optimization point is the point of the intersection between the line of the $\partial Mr/\partial Ur = 0$ and the horizontal line of the Cr upper limit. If the point of the intersection is not in the technical feasible range, the optimization point is the floor level value of the Ur and Cr), as O_{p1} and O_{p2} are shown in the Fig.4. Therefore, the example of the Harbin city, the economical ratio of the flux and velocity are respective that $Cr = 0.537 \sim 0.847$, $Ur = 0.33 \sim 0.4$.

In the Fig.4, the point O_{p1} is corresponding with $Mr = 4.34$, the point O_{p2} is corresponding with $Mr = 4.83$. It is obvious that when ((Ur, Cr) moves to the top left corner (bottom right corner), Mr will decrease (increase). It is also found by the research that when σ increases, that is the ratio of the investment increases, the two lines of $\partial Mr/\partial Ur = 0$ and $\partial Mr/\partial Cr = 0$ will move to the top right corner, which indicates the economical ratio of the flux increases. The economical ratio of flux and velocity due to different σ and the corresponding Hr and Mr are shown in the table 2. For the large engineering, Ur usually chooses smaller value, the corresponding Cr chooses bigger value.

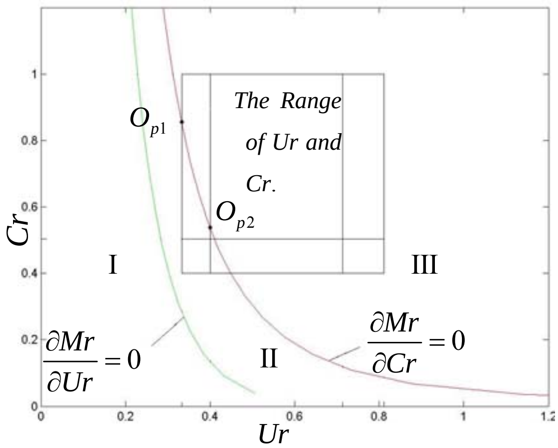

Fig.4 The economical ratio of flux and velocity

Tab.2 The economical ratio of flux and velocity different σ

σ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Cr	0.50 ~ 0.4	0.50 ~ 0.4	0.51 ~ 0.4	0.59 ~ 0.4	0.66 ~ 0.42	0.73 ~ 0.46	0.78 ~ 0.49	0.84 ~ 0.53	0.89 ~ 0.56	0.93 ~ 0.59
Ur	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4
Hr	0.26 ~ 1.34	0.26 ~ 1.34	0.26 ~ 1.34	0.34 ~ 1.34	0.41 ~ 1.36	0.48 ~ 1.43	0.56 ~ 1.49	0.63 ~ 1.55	0.71 ~ 1.61	0.78 ~ 1.68
Mr	1.88 ~ 2.23	2.24 ~ 2.60	2.61 ~ 2.97	2.96 ~ 3.34	3.30 ~ 3.71	3.63 ~ 4.06	3.95 ~ 4.42	4.27 ~ 4.76	4.58 ~ 5.09	4.89 ~ 5.43
σ	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Cr	0.97 ~ 0.62	1.00 ~ 0.65	1.00 ~ 0.68	1.00 ~ 0.70	1.00 ~ 0.73	1.00 ~ 0.75	1.00 ~ 0.77	1.00 ~ 0.79	1.00 ~ 0.81	1.00 ~ 0.83
Ur	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4	0.33 ~ 0.4
Hr	0.85 ~ 1.74	0.89 ~ 1.80	0.89 ~ 1.87	0.89 ~ 1.92	0.89 ~ 2.00	0.89 ~ 2.05	0.89 ~ 2.10	0.89 ~ 2.16	0.89 ~ 2.22	0.89 ~ 2.28
Mr	5.19 ~ 5.75	5.49 ~ 6.07	5.97 ~ 6.39	6.09 ~ 6.71	6.39 ~ 7.02	6.69 ~ 7.33	6.99 ~ 7.64	7.29 ~ 7.94	7.59 ~ 8.24	7.89 ~ 8.54

5. CONCLUTIONS OF FLOW RESISTANCE

By the above analysis, the thesis can gain important conclusions as follows:

5.1 Basing on the definition of equivalent fouling roughness height, the calculation method of the turbulent sewage resistance coefficient and the specific resistance of the different diameter of the pipes is obtained, which are shown detailed by the (2) and the table 1.The resistance of the urban sewage is 1.1~3 times bigger than that of mediate water., which lies on the roughness thickness of mediate water pipe wall.

5.2 By the contrastive analysis of the pump energy consumption of sewage and mediate water, it is known that because the equivalent diameter of the mediate water is small, the variational range of the flow resistance and the pump head is big, which are influenced heavily by the ratio of flux and velocity between mediate water and sewage, that is the emphases of the pipeline and the saving energy design for the TDHT system. The difference between other general system is that increasing the flux of the mediate water may reduce largely the systemic overall energy consumption, but it is the main means for the TDHT system to control the investment and the energy consumption.

5.3 The technical feasible ratio of flux and velocity are determined by the engineering restrictive analysis of the diameter of the pipe, the flux, the velocity, pump head, choosing model and construction, the range is that $0.4 \sim 0.5 \le Cr \le 1.0$, $0.33 \sim 0.4 \le Ur \le 0.72 \sim 0.81$.

5.4 The thesis gives the confirmation method and the character of the economical ratio of flux and velocity by economical optimization analysis of the investment and the function expenditure. For the general engineering, the economical ratio of the velocity is $0.54 \sim 0.85$, for the big engineering, Ur usually chooses smaller value, the corresponding Cr chooses bigger value. The ratio between the pump head of the mediate water and that of the sewage is $0.7 \sim 1.6$. The Fig.2 gives the range of the economical ratio of flux and velocity at the different investment and the function proportion.

The formula and the Figure of the thesis will afford academic reference for the pipeline design and the resistance calculation of the urban sewage double-pass TDHT system.

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