夹沙螺旋管流能耗的试验研究

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摘 要: 在水平圆管中设置导叶式起旋器, 使管内夹沙水流形成了强制螺旋流, 螺旋流可以分解为强制涡流与轴向平直流, 前者可起“抬托”泥沙的作用, 后者则同普通管道输送固粒一样起输移的作用, 这样使本来以推移质形式运动的泥沙较为容易地转变成悬移质。该文应用动量和动量矩定律, 对圆管内强制螺旋流的清水与夹沙两种情况进行了理论分析和试验研究, 得到的结论是: 螺旋管流的能坡可以用达西公式来表达; 其夹沙能力远高于同能坡下的平直流情况; 在非饱和状态下, 附加“旋浮”沙的能坡正比于含沙量。

关键词: 螺旋流; 输移; 固粒; 能耗

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传统的管道输移固粒均采用直流式(无旋流分量), 但该输送方式存在着低能耗与高浓度的矛盾。高浓度要求高速度的水流, 而高速度必然会产生高能耗, 这对于固粒(尤其是泥沙)的远距离输送是极为不利的, 特别对于自流式远距离输送, 更是无法实现。圆管螺旋流输移固粒则是另一种机理, 它具有浓度分布均匀, 使泥沙可达到均匀旋浮(有利于输移固粒), 能耗低的特点[1]。

螺旋流可分为强制涡流与轴向流。前者对固粒起“旋浮”作用, 使均匀固粒沿着同心圆轨迹运动, 而后者对固粒起输移作用。这样就将旋浮与输移分开, 消除了浮托对输移的依赖性, 从而可实现重载而缓行的输移方式, 能耗可大大降低。

1 螺旋流的形成

螺旋流是涡线与流线重合的一种特殊流动。由涡旋运动理论中的汤姆生(W. Thomson)定理和斯托克斯(G. G. Stokes)定理可知, 在理想流体中速度环量和旋涡都不能自行产生, 也不能自行消灭[2]。但实际流体——水是粘性的, 完全可以通过对水体施加某种无势力, 产生速度环量, 并利用粘性流体旋涡的扩散性[3], 使它形成涡强均匀的螺旋流。产生环量的一个简便方法是利用绕流叶型。当流体绕流不对称叶型或以正冲角绕流对称叶型时, 均能获得升力或环量[4]。为了在圆管中产生螺旋流, 可以在圆管中设置起旋器。起旋器是由若干导流叶片组成的环列叶栅, 它能将管内平直流有效地转变成螺旋流。

1.1 多导叶起旋器[5]

初期试验设计的起旋器是沿圆管直径连续布置的通心扭曲叶片(叶片宽度等于管内经, 管内经 d = 12 cm)。该器产生的螺旋流因“局部”效应使管内流速呈现非均匀的特性。这一特性由于速度的重新分布而产生额外的能量损失。同时由于叶片数少, 其背面易产生脱离, 形成涡流, 从而增加了水头损失。因此, 在第二阶段的试验中, 将叶片数增至 4 片, 叶片安放角 A仍取 20°, 高度 $b = d/3 = 4$ cm、长度 $l = 18$ cm、厚度 D= 5 mm (其形状如图 1 所示), 将其装在管周形成均匀的环列叶栅。

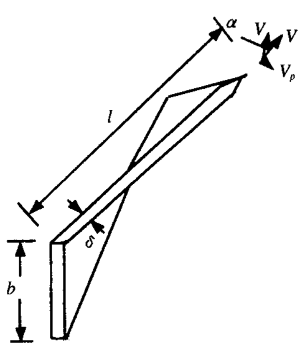

图 1 叶片形状

Fig. 1 Shape of blade

1.2 起旋器对水流的作用

由于导叶排成环列叶栅, 中部留空, 对水流不产生任何阻力, 水流从中空部分直通而过。在布有导叶部分的外环中, 由于导叶的作用, 水流将受到逆流向的阻力与垂直向的升力。阻力将使叶片入口处的压力升高, 致使外环中的水体有了向中空部分挤压的现象。这一现象将使中空部的水流加速。与此同时, 外环中的水流在升力的作用下, 产生扭转现象。在 4 个叶片的协同作用下, 外环中的水流开始绕管轴转

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动形成螺旋流。不过, 由于叶片数量有限, 这种转动并非均匀一致, 即在叶片的迎流面, 水体的转动效果比背流面好, 叶片近处的转动效果比远处的好。从理论上讲, 只有无穷多且沿管壁连续布设的叶片才能消除这种不均匀性, 但实际设计中, 只能取一定的叶片数, 这要由试验来确定。同时, 叶片的安放角 α、高度 b、长度 l 及厚度 δ 亦均需由试验确定。

2　力学分析

由水力学原理可知, 导流叶片的迎流面承受流体的压力要比背流面大, 即它对水流产生一个压力差。这就是形成螺旋流的基本力。

2.1　螺旋流的运动学特征

螺旋流中的轴向流与一般管流相同, 可分为近壁层流低层与流核两部分(忽略过渡区)。为了便于分析, 可假定流核中速度均匀, 而层流低层中速度为线性分布。横向旋流同样可分为层流低层与流核两部分, 流核中的速度假设为按强制涡规律分布, 而层流低层中的速度按线性分布。这样螺旋流在管壁上产生的切应力由强制涡的最大周向速度来决定。而轴向流则由平均流速来决定, 可用轴向平均流速 U 与周向最大速度 ω_{max} 来表征螺旋流的运动学特征, 两速度可合成为速度矢量 V。

2.2　螺旋管流的动力学特征

除具有压管流的一般动力学特征外, 它需加上导流壁对水流的作用力及管壁对旋流的周向剪切力。

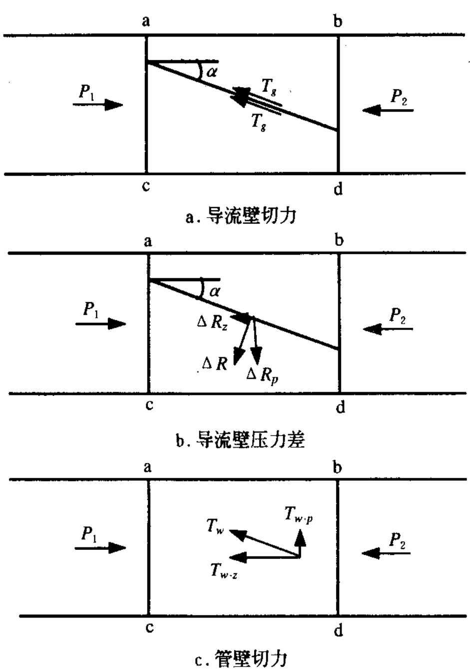

图 2　螺旋管流受力分析

Fig. 2　Stress analysis in spiral pipe flow

如图 2 所示, 取控制体 $abcd$, 导流壁对水流的作用力有切力 T_g 与压力差 ΔR。切力 T_g 沿导流壁方向, 由两边壁作用于水流(如图 2a)。它又可分解为轴向分量 $T_{g\cdot z}$ 与周向分量 $T_{g\cdot p}$, 分别阻碍轴向水流与旋流。压力差 ΔR 垂直于导流壁, 是由于迎流面与背流面的压力差产生的。它可分解为轴向分量 ΔR_z 与周向分量 ΔR_p(如图 2b), 前者阻碍轴向水流, 而后者则是保持旋流的原动力。管壁摩擦力 T_w 可分解为轴向分量 $T_{w\cdot z}$ 与周向分量 $T_{w\cdot p}$(如图 2c), 前者阻碍轴向水流, 而后者阻碍旋流, 同时与导流壁压差的轴向分量 ΔR_p 达成平衡。此外, 在控制面 ac 与 bd 上分别作用有压力 P_1 与 P_2。在水平管道情况下, 不考虑重力, 应用动量定律与动量矩定律于控制体 $abcd$, 由于进出控制体的流速不变, 从而可得力与力矩平衡方程

$$P_1 - P_2 = 2T_{g\cdot z} + T_{w\cdot z} + \Delta R_z \tag{1}$$

$$T_{w\cdot p}\cdot r + 2T_{g\cdot p}\cdot r/2 = \Delta R_p\cdot r/2 \tag{2}$$

式中　r—— 管道半径。

由几何关系知, $\Delta R_z = \Delta R_p\cdot \mathrm{tg}\alpha$, α 为流核外围的水流偏折角(可视为叶片的安放角), 将它与式(2)同时代入(1) 可得

$$P_1 - P_2 = 2T_{g\cdot z} + T_{w\cdot z} + 2(T_{w\cdot p} + T_{g\cdot p})\mathrm{tg}\alpha = 2T_{g\cdot z}(\mathrm{tg}^2\alpha + 1) + T_{w\cdot z}(2\mathrm{tg}^2\alpha + 1) \tag{3}$$

在安放角较小时(本试验取 $\alpha = 20°$), 由于 $2T_{g\cdot z} \ll T_{w\cdot z}$, 式(3) 可近似地表达为

$$P_1 - P_2 = (2T_{g\cdot z} + T_{w\cdot z})(2\mathrm{tg}^2\alpha + 1) \tag{4}$$

式中　$2T_{g\cdot z} + T_{w\cdot z} = T_z = T\cos\alpha = A\tau$, 面积 A 包括管壁与导流叶片壁两侧面, 即 $A = L(2\pi r + 2\times d/3) = 2rL(\pi + 2/3)$。切应力 τ 与水流速度 U 的二次方成正比, 即 $\tau = k\rho U^2\sec^2\alpha$, 代入式(4) 得

$$\pi r^2(P_1 - P_2) = 2rL(\pi + 2/3)k\rho U^2\sec^2\alpha(2\mathrm{tg}^2\alpha + 1)$$

$$J_s = 2(\pi + 2/3)k\rho U^2\sec^2\alpha(2\mathrm{tg}^2\alpha + 1)/\pi r\rho g = \frac{\pi + 2/3}{\pi}(\sec^4\alpha + \sec^2\alpha\cdot\mathrm{tg}^2\alpha)\frac{k_1}{R}\frac{U^2}{2g} \tag{5}$$

式中　$k_1 = 2k/\pi$, k—— 切应力系数; ρ—— 流体密度; L —— 控制体长度; R —— 水力半径 $R = d/4$; g —— 重力加速度; 其余符号意义同前。

上式表明, 强制螺旋流的水力坡度 J_s, 完全可以利用管流达西公式进行表达, 只要进行流速水头 $U^2/2g$ 与水力半径 R 的修正即可, 故式(5) 可表达为

$$J_s = k_U K_R k_1 U^2/2g \tag{6}$$

式中, 流速水头的修正系数 $k_U = \sec^4\alpha + \sec^2\alpha\mathrm{tg}^2\alpha$, 水力半径的修正系数 $K_R = (\pi + 2/3)/\pi = 1.212$。$\alpha = 20°$ 时, $k_U = 1.433$。设 $k' = k_U K_R = 1.736$, 则 $J_s = 1.736k_1U^2/2g$。

2.3　强制螺旋流输移固粒时的能耗

这种情况应该是上述情况再加一个“旋浮”功率。因固粒群在有效重力的作用下以沉速 X 下沉, 在旋流作用下, 才保持“旋浮”平衡, 而旋流是在导流壁的压力差 $R 作用下才得以维持的, 设固粒群的极限轨迹圆的圆心 O 偏离管轴心 O' 的距离为 E= XöH[6] (H为旋流的转动角速度), 由合力矩定理可推知, 固粒群对管轴心的合力矩 M_G 可以由其有效重力的合力 G_e 与圆心的偏心距 E的乘积来决定, 即 $M_G = G_e \times$ E。该力矩将由 $R 中的一部分 $R_1 产生的旋转力矩 M_R 来平衡。由 2.2 分析可知 $R_1 的作用类似于前述 $R, 因此它将影响水流的能耗。因 $M_R = M_G = G_e \times$ E, 可见因“旋浮”所作的功正比于固粒的有效重力 S 与沉速, 而反比于旋流的转动角速度 $W_s = KS$ XöH, K 为比例系数。

“旋浮”功正比于沉速是比较合理的。例如, 当沉速 X 为零时, 泥沙自然不下沉, 也就不需水流对其作“旋浮”功。当 X= X_{max} 时, 泥沙平衡于水平半径的一端, 其“旋浮”功即为 G_e1　X_{max}。但对于 $W_s \propto S$, 却仍存在若干疑点: 第一, 上述分析忽略了水流的紊动作用; 第二, 分析是对均匀粒径的固粒来说的, 对于非均匀固粒, 则必须考虑细粒径的粘性作用与对重度的影响。即粗颗粒在细颗粒的包围之中, 要受到较清水中更大的浮力与阻力。因此当含沙量达到一定值时, 这种影响就会反映出来。总之, 需要通过试验找出 $W_s \sim S$ 的确切关系。

3　试验结果

3.1　强制螺旋流的能坡

试验是在一个由平直流管与螺旋流管串联的循环系统中进行的。系统中还设有沉沙箱、混沙器、水位稳定装置。系统工作由水泵供给水源。平直流管内径为 9 cm, 试验段长为 7 m, 管材系 PVC 管; 螺旋流管内经为 12 cm, 试验段长为 5 m, 管材系有机玻璃管。两种管材的糙率均为 0.009, 在平直流情况下, 两种管径水力坡度比值为 $K = K_r^{-1.333} K_r^{2} = K_r^{-5.333} = (12ö9)^{(-5.333)}$。而螺旋流(A= 20°)与平直流的水力坡度比值由前节可知 $k' = 1.736$, 故平直流小管与螺旋流大管的能坡比应为 4.638ö1.736 = 2.67。

试验结果列于表 1 中。由表中可见:

1) 两管的能坡比的平均值为 2.73, 与理论计算值 2.67 的相对误差仅为 2.2%。微小的差别可能是由于两管的实际糙率的差别及模型制作方面的原因引起的。

2) 流量对能坡比没有明显的影响, 这说明两管的流动均属于成熟紊流。因此, 在分析夹沙螺旋流时, 应充分估计水流的紊动作用。

表 1　螺旋管流与平直管流的能坡比

Table 1　Energy gradient between spiral pipe flow and straight pipe flow

流量 QöL·s^{-1}	管别	流速 Uöm·s^{-1}	水头损失 $h_f$öcm	能坡 Jö%	能坡比 $J_É$ö$J_°$
3.55	É	0.56	3	0.43	2.87
	°	0.31	0.75	0.15	
4.96	É	0.78	5	0.71	2.63
	°	0.44	1.35	0.27	
6.22	É	0.98	6.6	0.94	2.69
	°	0.78	5	0.71	
7.28	É	1.14	8.2	1.17	2.72
	°	0.64	2.15	0.43	

注: É 为 d = 9.0 cm, 管长 L = 7.0 m 平直流;
° 为 d = 12 cm, 管长 L = 5.0 m 螺旋流。

3.2　螺旋流夹沙的“旋浮”能坡

在前述的管道系统中进行输沙能耗试验。为保证在管道系统中不发生淤积, 在每加完一组沙时, 调节水泵阀门, 使管系中夹沙能力达到同一种情况: 平直流管中处于饱和夹沙情况, 而螺旋流管处于非饱和态。待稳定后量测两试验管段的水头损失及流量, 求得螺旋流夹沙情况下的能坡与流量关系(见表 2)。

表 2　非饱和夹沙螺旋管流能坡表

Table 2　Energy gradient of spiral pipe flow with unsaturated grain

流量 QöL·s^{-1}	管别	水头损失 $h_f$öcm	能坡 Jö%	能坡比 $J_É$ö$J_°$	含砂量* Sökg·m^{-3}
5.05	É	5.15	0.74	2.55	16.7
	°	1.45	0.29		
5.60	É	5.92	0.84	2.80	25.0
	°	1.50	0.30		
6.10	É	6.62	0.93	2.38	33.3
	°	1.95	0.39		
6.95	É	7.82	1.05	1.98	41.6
	°	2.65	0.53		
7.28	É	8.20	1.17	2.02	50.0
	°	2.90	0.58		

* 由加砂量扣除沉砂箱淤积量除以系统体积求得, 并以管道淤积量进行核对。该值只有定性的指导意义。

分析表 1、表 2 可知, 螺旋管流“旋浮”沙粒时, 确需消耗附加能量, 且它与含沙量近于 1 次方关系。鉴于目前设备条件限制, 还不具备进行高含沙输移试验的条件, 相应规律有待进一步研究, 但就目前的试验结果, 可以肯定以下几点: 1)“旋浮”能耗正比于含沙量; 2) 螺旋管流非饱和夹沙时的能耗远低于平直流饱和夹沙时的能耗; 3) 螺旋流的夹沙能力远大于同一能坡下的平直管流。

4 结　论

1) 螺旋流可通过管内环列叶栅产生。

2) 螺旋管流的能坡可以用达西公式表达, 只要乘以水力半径修正系数与流速水头的修正系数即可。

3) 螺旋管流的挟沙能力远远高于同能坡下的平直管流, 在非饱和状态下, 其附加"旋浮"沙的能坡正比于含沙量。

4) 高含沙输移的能耗具有重要的工程应用价值, 需要进一步进行试验研究。

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Coordinating of Root-Water-Fertilizer Relation of Spring Wheat-Spring Corn Intercropping System Under Regulated Deficit Irrigation ········· (53)

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Abstract: Determining coordinating of Root2Water2Fertilizer relation was studied. Two crops of spring wheat and spring corn intercropped were grown in cement pool with length of 1 m, width of 1 m and depth of 1.5 m. The regulated deficit irrigations (RDI) of 30%, 50% and 70% of soil relative water content (SRW) were performed at later jointing stages for spring wheat (seedling stages for corn). Total seed yield of intercropping system was increased with 50% of SRW under 50% RDI at seedling stages for corn intercropped. The vertical distribution of soil Olsen2P and root weight decreased significantly from surface soil layers to deep layers, above 30% of Olsen2P and 40% of root dry mass in 0～100 cm soil depths were distributed in 0～10 cm soil layer, but where the water content is always below 10%, so un2coordination of soil water with root and soil Olsen2P in soil layers reduced nutrition use efficiency (NUE). RDI and deep P supply increased amount of roots of below 40 cm soil depths, which was favorable to absorb nutrient for roots in deeper soil profile at the middle and later growth stage. Spatial distribution of NO_3^- 2N and NH_4^+ 2N were influenced by irrigation, at the first period of growth, NO_3^- 2N and NH_4^+ 2N mainly distributed on the 0～10 cm soil layer, but which gradually moved to deep soil along with crop growth, therefore, nitrogen fertilizer should not be applied at deep soil layer, and should be supplied with several times.

Key words: regulated deficit irrigation (RDI); spring wheat2spring corn intercropping system; root2water2fertilizer relation

Preliminary Study on Effects of Roots-Divided Alternate Irrigation on Nutrient Uptake by Maize ········· (57)

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Abstract: Effects of roots2divided alternate irrigation on nutrient uptake were studied with controlled alternate irrigation (CAI) for half part of root zone, controlled fixed irrigation (CFI) for half part of root zone and conventional irrigation (CI) for whole root zone. The results showed total N uptake of CAI was higher than that of CFI, but there is no difference compared with CI at early jointing stage. But at the end of maize development, the total N uptake of CAI treatment was higher than that of CFI and CI. And total P uptake in CAI treatment was higher than that of the other two irrigation methods. Compared with CI treatment, plant N and P use efficiency in CAI treatment was enhanced by 25.1% and 25.3%, respectively. In CAI treatment, irrigation water was saved by 10.3% compared with CI, water use efficiency was the highest among the three irrigation treatments, and increased by 20.1% compared with CI.

Key words: alternate irrigation; maize; nutrition

Experimental Study on Energy Gradient of Sediment Transportation in Spiral Pipe Flow ········· (60)

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Abstract: Forced spiral flow can be produced in a circular pipe flow by erecting blades in the pipe. The velocity of spiral pipe flow with sediment can be decomposed into the circumferential vortex flow velocity and the axial flow velocity as normal pipe flow. The former acts as uplifting the sediment and the latter transports it. Therefore the transported sediment with the form of bed load can be changed as suspended load easily. In this paper, with the momentum law and the momentum moment law, the forced spiral flow was analysed and studied in theory and by experiment, which was in two states of clean water and sediment2laden water separately. The obtained results are: the energy gradient of spiral pipe flow can be expressed with Darcy's equation; it has more ability of sediment transportation than normal pipe flow at the same energy gradient; the additional energy gradient of uplifting sediment is proportional to the sediment concentration in water. It lays a reliable basis for studying sediment transportation in spiral flow.

Key words: spiral flow; transport; sediment; energy consumption

Equation of Friction Loss Along the Plastic Pipe of Micro-Irrigation System ………… (64)

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Abstract: The equation for friction loss along the plastic pipe of micro2irrigation is presented adopting the multiple2regression analysis according to existing friction loss equation. The new equation is superior to existing equation in calculated results owing to considering pipe diameter, flow velocity and water temperature at the same time. The calculated result is more precise. The error analysis shows that the equation is satisfied with the requirement of project design. The developed equation can be employed in the design of micro2irrigation pipe system.

Key words: plastic pipe; micro2irrigation; friction loss computing

Application of TC-30 Digital Water-level Monitoring Transmitter in Agricultural Water Conservancy Project ……………………………………………………………………… (67)

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Abstract: The pressure2type stage sensor, float2type stage sensor and capacitance2type stage sensor are widely used in agricultural water conservancy project in China. However, there exists some drawback when they are equipped in the project with hyper2concentration of sediment and swift flow, in which collecting message requires remote telemetry. It is an inevitable tendency to use modern computer technologies to explore the higher accuracy and highly adaptable devices of water2level measurement in the agricultural water conservancy project. TC2301 new type stage sensor is presented in this paper, it practices new thought of simulative nerve theory, which succeeds in achieving new breakthrough in measuring water2level of agricultural water conservancy project, and the application effect is good.

Key words: agricultural water conservancy; computer; digital water2level transmitter

· Agricultural Machinery and Mechanization Engineering ·

Soil Nitrogen Loss in Runoff and Sediment as Affected by Level Trench and Crop Rotation ……………………………………………………………………………………… (70)

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Abstract: Compared with conventional tillage, level trench might reduce 7% in average of runoff amount on different slope land, the ammonium concentration in runoff increases 19%, its loss amount reaches 13.01 kgö(km^2 · a), also increases by 1.11 kgö(km^2 · a), the nitrate concentration in runoff reduced 27%, its loss amount is 16.18 kgö(km^2 · a) with reduction of 7.68 kgö(km^2 · a), in conclusion, the soil available nitrogen loss in level trench might reduce 6.57 kgö(km^2 · a) than that of conventional tillage. Level trench might retain 25% of soil loss, increase 13% of total nitrogen enrichment in sediment than that of conventional tillage, accordingly, soil nitrogen loss amount reaches 457 kgö(km^2 · a), it also reduces 13% of nitrogen loss than that of conventional tillage. Five years' rotation experiments show the erosion modules of rotation systems with a season black soybean, a season soybean, and two seasons black soybean, a black soybean, reach 896 and 984 tö(km^2 · a) respectively, their modules are twice less than that of rotation system with broom millet and potato.

Key words: level trench; crop rotation; soil nitrogen loss

Computerized Simulation of Working Process of Seed Metering Device for 2BQM-2 Plastic Film Mulch Pneumatic Precision Planter ……………………………………………………… (74)

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Abstract: An analysis of the process of punching holes on the plastic film, grasping at the seed through suction holes, dropping off the seed and the operation mechanism of the 2BQM22 model plastic film mulch