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超临界CO_2膨胀机涡轮气动设计优化

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清 华 大 学

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清华大学热流体研究团队简介

• 张扬军 教授、博士生导师，长江学者特聘教授

- ◆ 汽车安全与节能国家重点实验室常务副主任、清华大学通用航空技术研究中心主任
- ◆ 军委科技委xx专家组专家，军委装备发展部xx专业组专家
- ◆ 国际杂志I. J. of Fluid Machinery and Systems 主编
- ◆ 获国家科技进步二等奖2项（排名1，3），国防科技进步一等奖等省部级奖9项

• 诸葛伟林 副研究员、博士生导师

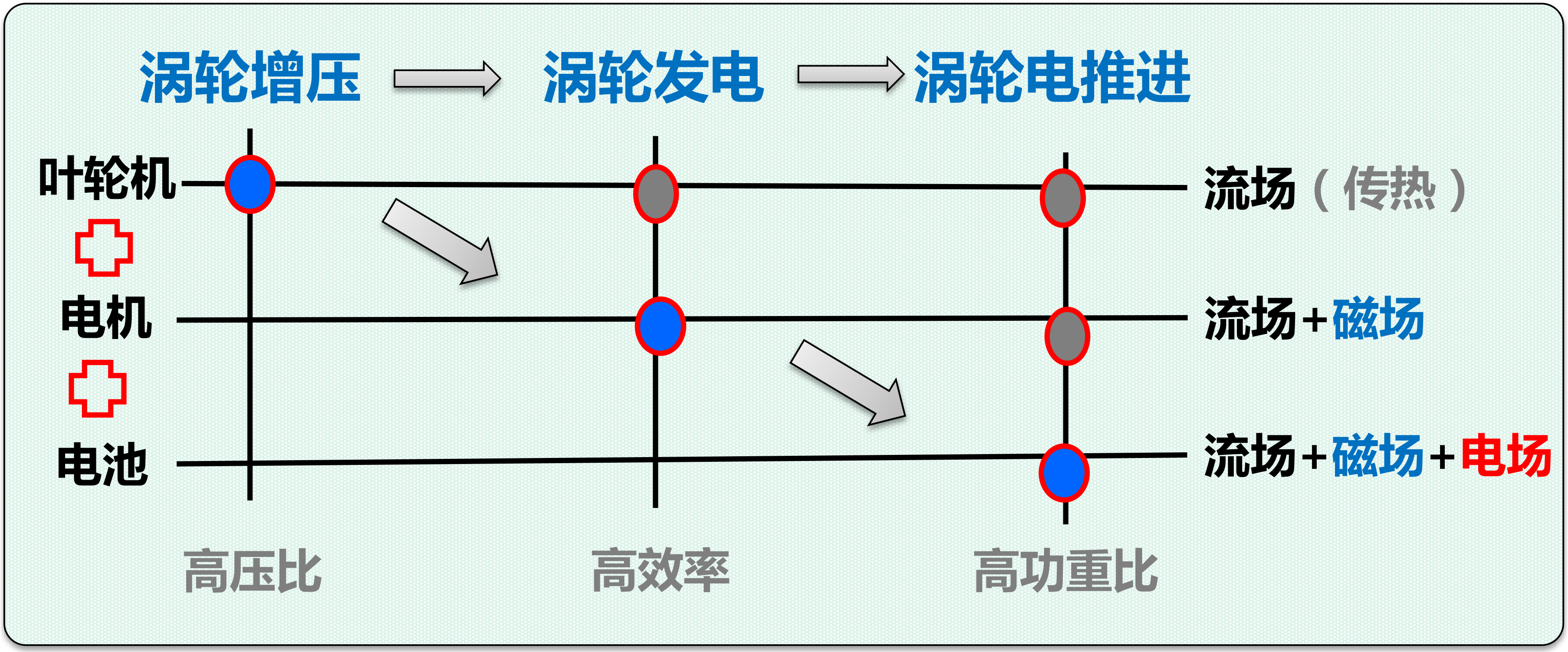
- ◆ ASME 国际燃气轮机学会 ORC 动力系统委员会委员
- ◆ 中国兵工学会发动机委员会委员，中国内燃机工业协会增压器分会技术委员会委员
- ◆ 《内燃机学报》编委、《船舶工程》编委
- ◆ 获国家科技进步二等奖1项（排名5），国防科技进步一等奖等省部级奖5项

• 钱煜平 助理研究员、硕士生导师

- ◆ 主持国防973项目专题研究3项
- ◆ 牵头研制的国内首架电动涵道风扇无人机参加“第二届军民融合发展高技术成果展”
- ◆ 清华-亚琛协同创新“航空混合电推进项目”中方技术负责人

研究方向与关键技术

- 研究方向：发动机热流体工程（热力学、流体力学与控制工程交叉融合）
- 关键技术：涡轮增压、涡轮发电与涡轮电推进



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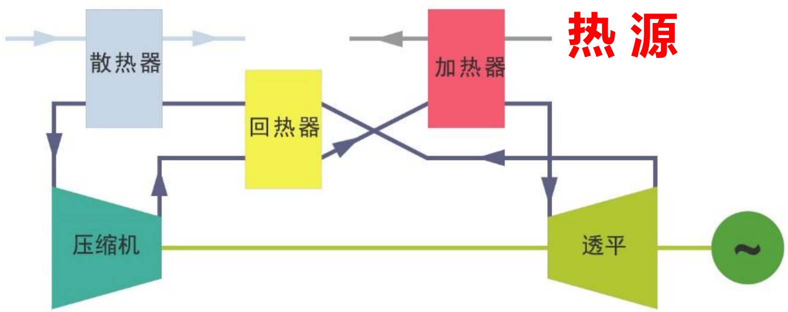
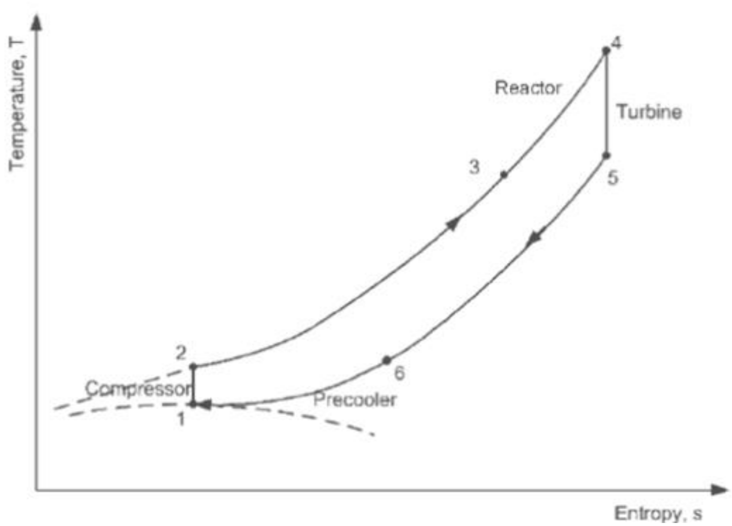
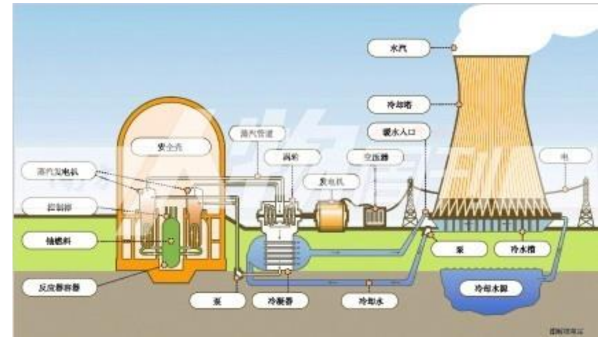
- 超临界CO_2动力循环
- 膨胀机涡轮气动设计
- 膨胀机进气蜗壳优化
- 膨胀机涡轮叶型优化

超临界CO_2动力循环

超临界CO_2动力循环原理

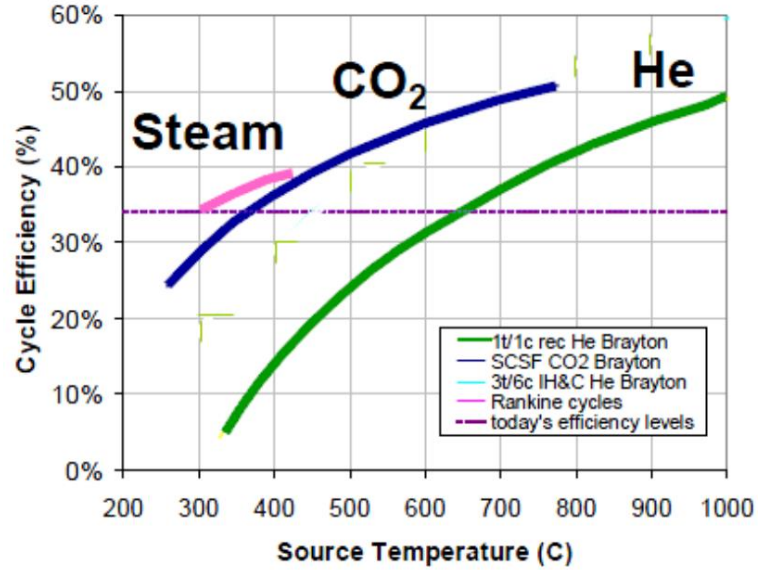


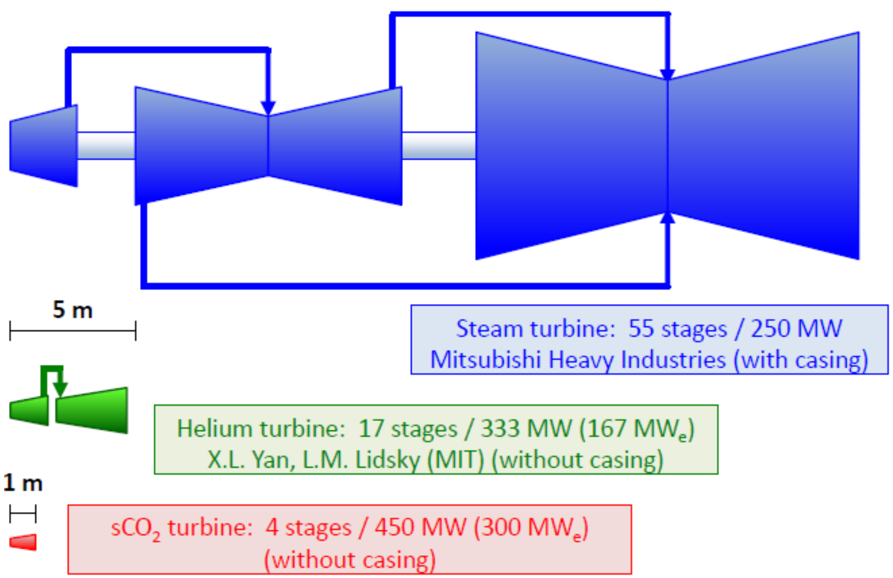


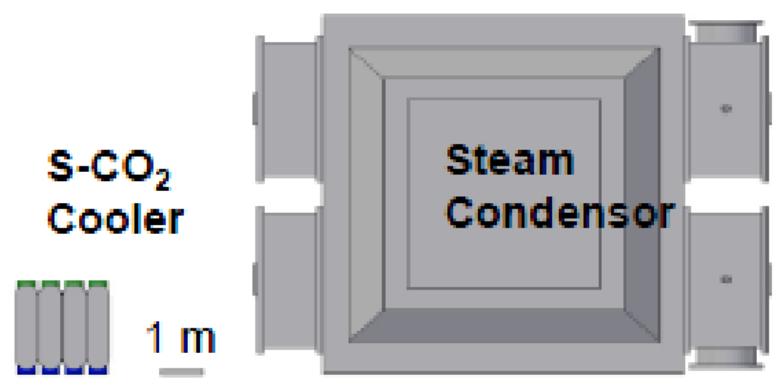


超临界CO_2动力循环特点

- 功率密度高
- 高温特性好
- 循环效率高





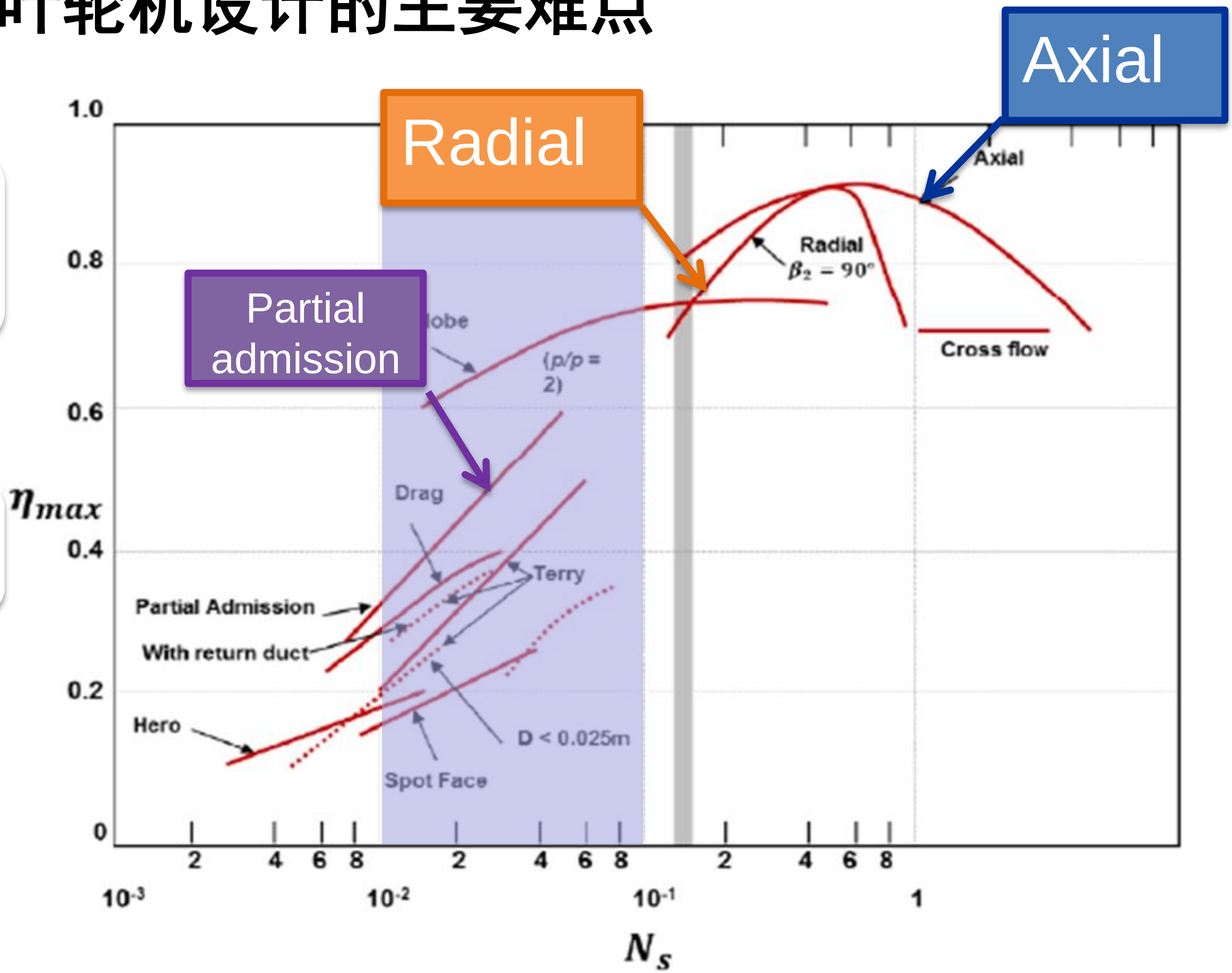


超临界CO_2叶轮机设计的主要难点

小流量
高焓降

低比转速

$$N_s = \frac{\omega\sqrt{Q}}{\Delta h^{3/4}}$$



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- 膨胀机涡轮叶型优化

膨胀机涡轮气动设计

涡轮叶片参数设计

选取流量系数、功率系数与反动度：

$$\phi = \frac{C_m}{U} \qquad \varphi = \frac{\Delta h}{U^2} \qquad R = 0$$

$$C_{\theta 3} = (1 - R + \varphi / 2)U$$

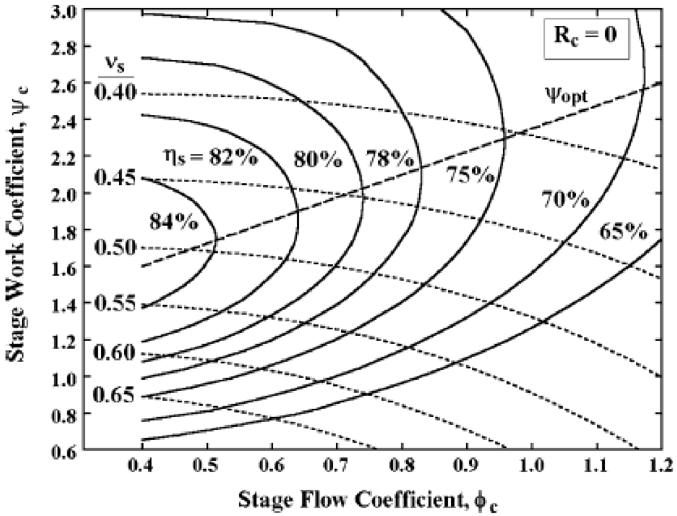
$$C_{\theta 4} = (1 - R - \varphi / 2)U$$

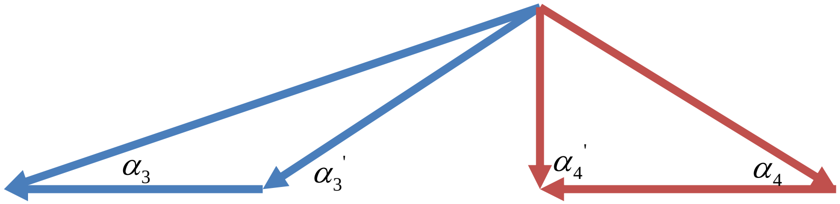
$$\cot\alpha_2 = \cot\alpha_3 = [1 - R + \varphi / 2] / \phi$$

$$\cot\alpha_3' = [-R + \varphi / 2] / \phi$$

$$\cot\alpha_4 = [1 - R - \varphi / 2] / \phi$$

$$\cot\alpha_4' = [-R - \varphi / 2] / \phi$$

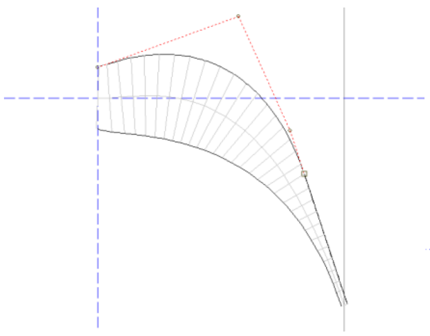




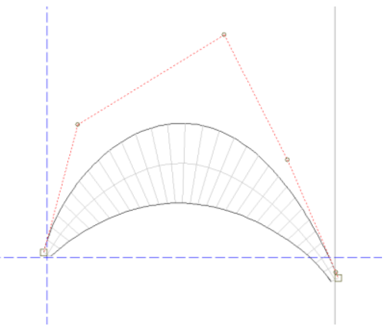
速度三角形

涡轮叶型初步设计

- 根据速度三角形确定静叶和动叶进出口角度
- 通过贝塞尔曲线控制叶型，实现参数化

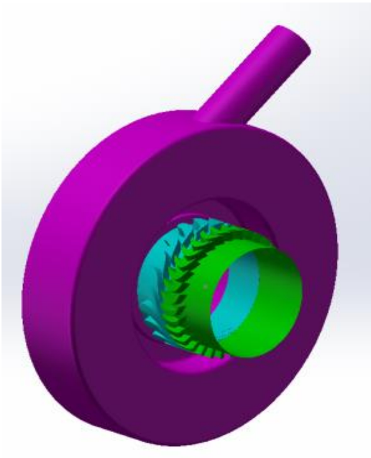


静叶叶型



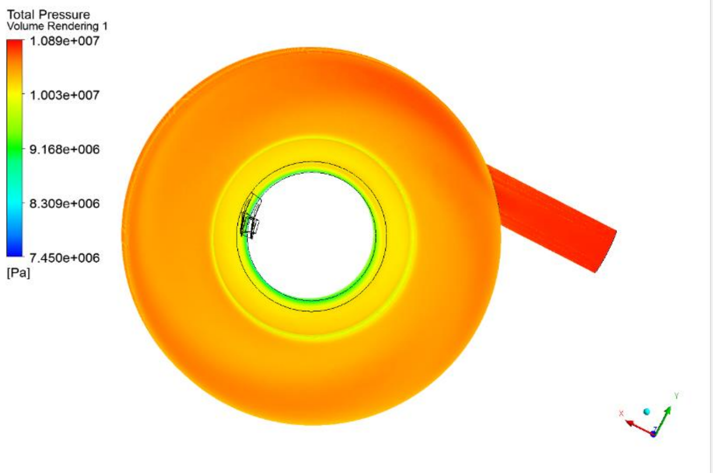
动叶叶型

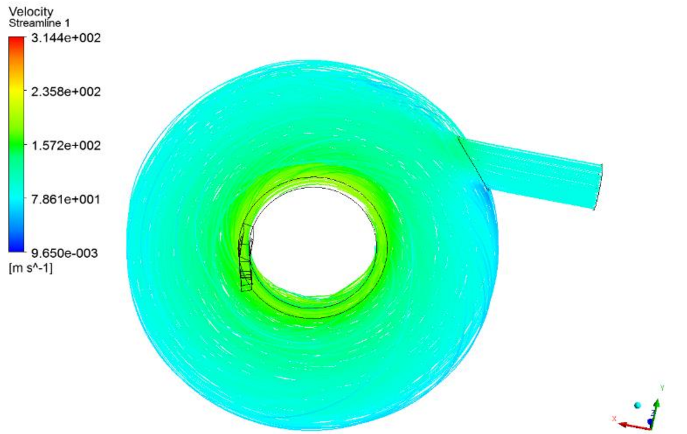
	入口角	安装角	出口角
静 叶	0	40	70
动 叶	60	5	60



■ 涡轮性能及流场分析

进气度	功率	效率
2.8%	5 kW	56%
16%	30 kW	69%
100%	100 kW	31%

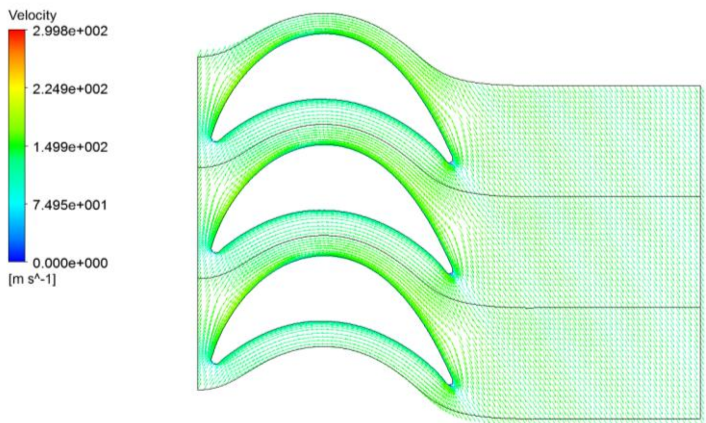


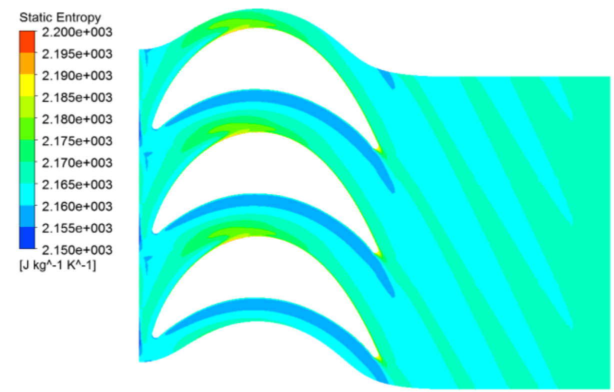


- 全周进气时涡轮效率大幅降低，主要由于进气蜗壳总压损失较大，达到进口总压的 9.8%.

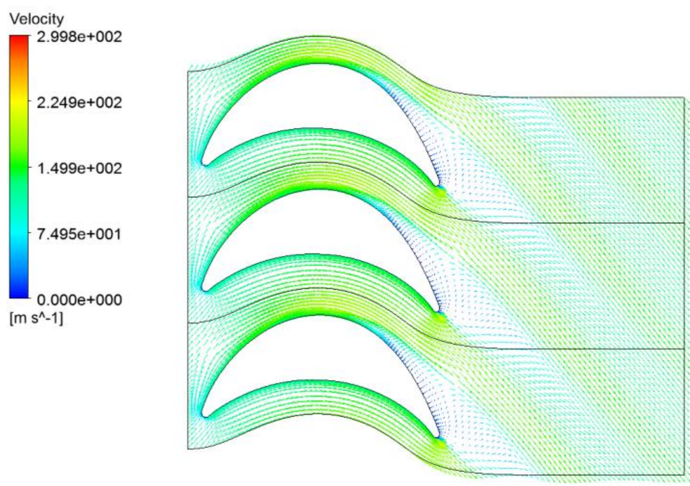
- 动叶叶顶间隙泄漏流动导致吸力面靠近出口附近出现流动分离，流动损失增大

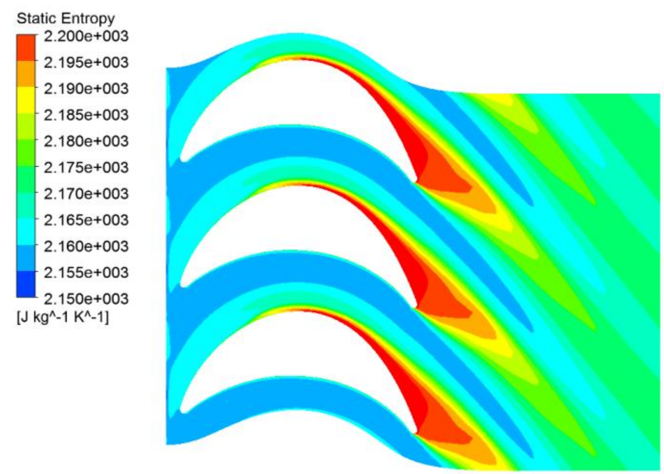
叶根流场



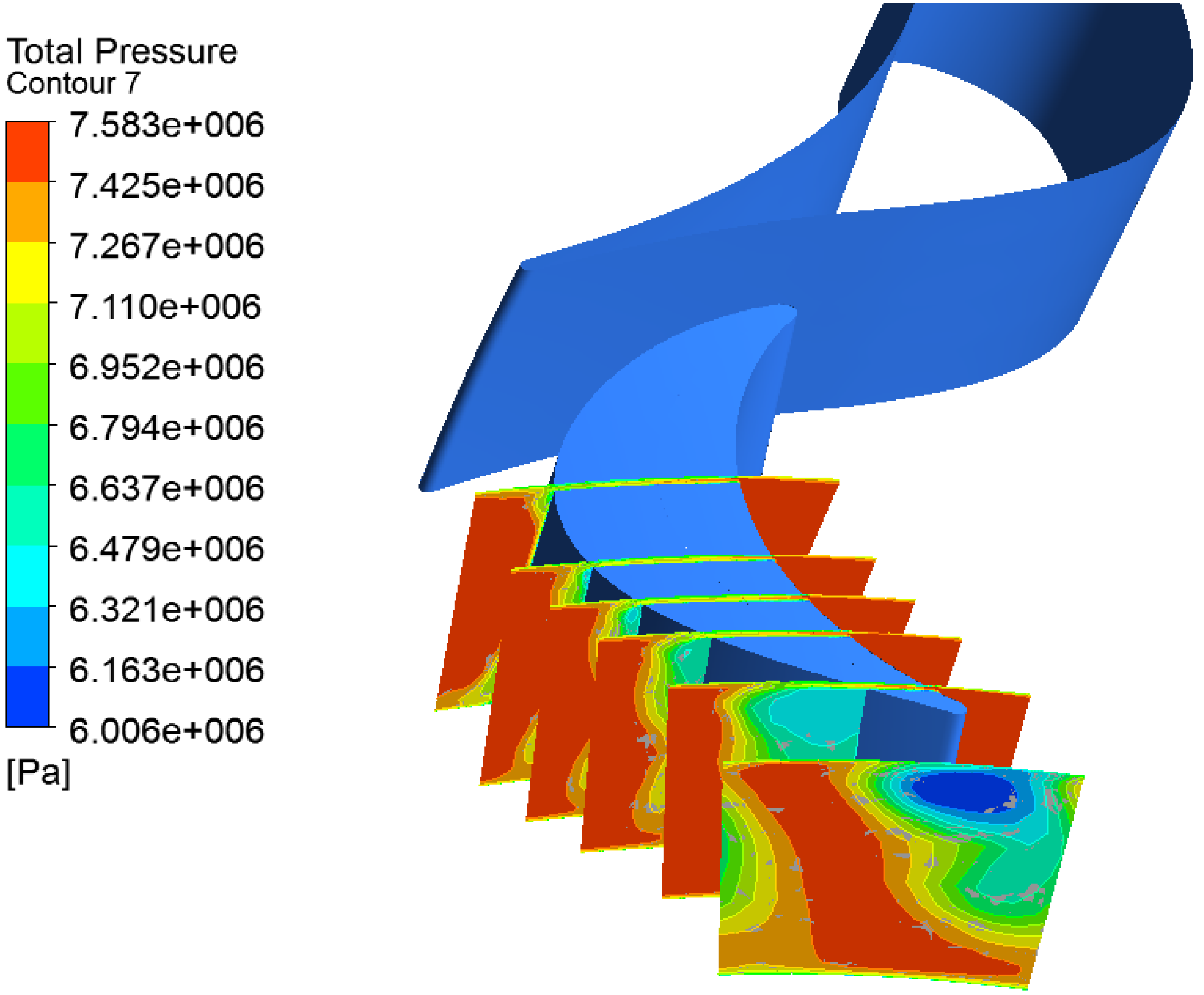


叶尖流场





- 动叶叶顶间隙涡的演变



Total Pressure
Contour 7
7.583e+006
7.425e+006
7.267e+006
7.110e+006
6.952e+006
6.794e+006
6.637e+006
6.479e+006
6.321e+006
6.163e+006
6.006e+006
[Pa]

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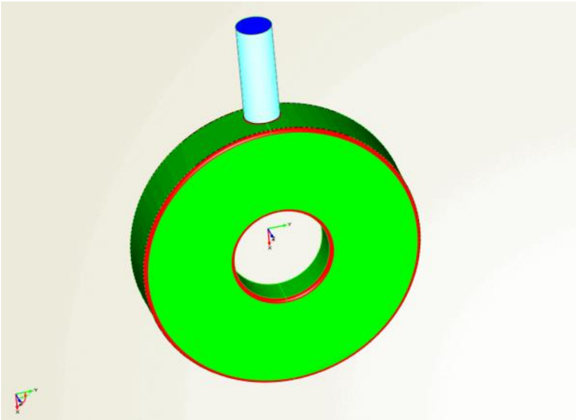
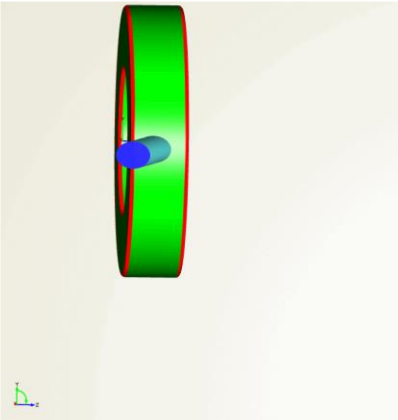
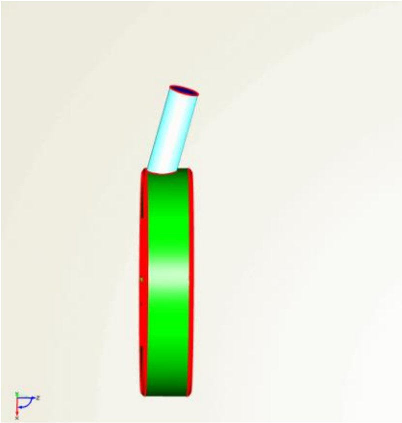
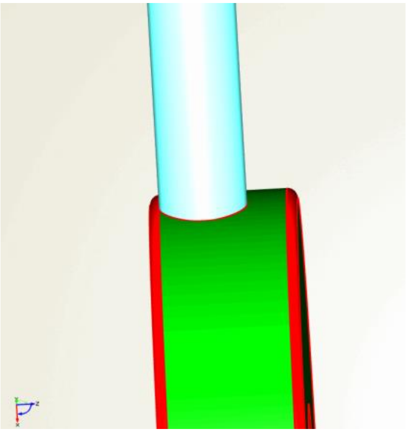
膨胀机进气蜗壳优化

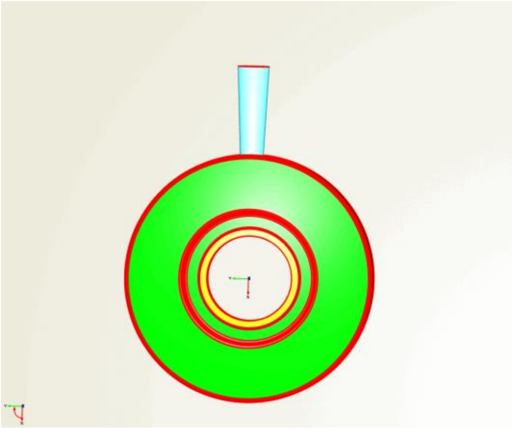
■ 进气蜗壳优化参数


入口切向角度


截面形状


入口轴向角度


入口轴向位置


进口管扩张度

■ 优化方法

- 利用CASES软件，采用遗传算法进行优化，经过5代优化，每代8个。采用8核计算平台，耗时26小时。

Show Charts

	Angle	Ellipse_A	Ellipse_B	Rotor_Gama	offset_coeff	Z_position	eval_ResultsValue_00
Nsga2_02_des0000	-17.089952	9	19.25594	-5.8062104	1.4750607	5.838011	-0.678
Nsga2_02_des0001	-14.944839	9	14.90779	-0.45883879	1.2327031	4.5360243	nan
Nsga2_02_des0002	-33.085603	9	9.9435416	-7.6293584	1.6740627	6.068954	-0.505
Nsga2_02_des0003	-8.8370336	9	19.014755	-5.8852522	1.9297139	2.5767773	-0.704
Nsga2_02_des0004	-13.489128	9	13.827909	-5.4830243	3.4765621	4.3116869	nan
Nsga2_02_des0005	-30.604715	9	8.3768063	4.[illegible]	1.7810666	2.8529435	-0.47
Nsga2_02_des0006	-15.553216	9	17.823362	6.[illegible]	2.4050629	3.950325	-0.698
Nsga2_02_des0007	-9.3877317	9	7.8403906	2.7190051	2.5705287	3.8026299	-0.647
Nsga2_02_des0008	-14.461433	9	19.261067	-5.8855573	1.810222	5.8397047	-0.692
Nsga2_02_des0009	-11.465553	9	19.009628	-5.8059052	1.491426	2.5750835	-0.692
Nsga2_02_des0010	-9.3877317	9	7.7583581	3.6174563	2.4931838	6.0681918	-0.645
Nsga2_02_des0011	-33.085603	9	10.025788	-8.5278096	1.7514076	3.8033921	-0.519
Nsga2_02_des0012	-33.085603	9	10.162295	-7.6293584	2.2638178	5.9388739	-0.583
Nsga2_02_des0013	-14.944839	9	14.90779	-0.45883879	0.84920119	4.6661044	-0.64
Nsga2_02_des0014	-8.8507668	9	19.038682	-5.807126	1.9295125	3.7908583	-0.704
Nsga2_02_des0015	-17.076219	9	19.232013	-5.8843366	1.4752621	5.3176905	-0.68
Nsga2_02_des0016	-20.123598	9	19.026505	-5.8077363	2.4050629	3.9508638	nan
Nsga2_02_des0017	-4.2803845	9	17.835538	6.2243076	1.9295125	3.7905196	-0.711
Nsga2_02_des0018	-11.641337	9	15.511284	-5.8059052	1.1047013	2.7505562	-0.668
Nsga2_02_des0019	-8.6749828	9	19.036973	-5.807126	2.3162371	3.615555	-0.716
Nsga2_02_des0020	-3.2119478	9	19.01561	-5.8852522	1.8104738	2.5767773	-0.717
Nsga2_02_des0021	-20.086519	9	19.260212	-5.8855573	1.9294621	5.8397047	-0.685
Nsga2_02_des0022	6.9835203	9	18.919905	-5.6508736	2.4050629	2.5767773	-0.732
Nsga2_02_des0023	-31.37377	9	17.919066	5.9893187	1.9297139	3.950325	nan
Nsga2_02_des0024	-3.2119478	9	19.014755	-5.8852522	1.8136965	2.5767773	-0.718
Nsga2_02_des0025	-8.8370336	9	19.01561	-5.8852522	1.9262898	2.5767773	-0.705
Nsga2_02_des0026	-8.8370336	9	19.038682	-5.807126	1.9297139	2.5767773	-0.704
Nsga2_02_des0027	-8.8507668	9	19.014755	-5.8852522	1.9037308	3.7908583	-0.704
Nsga2_02_des0028	6.9835203	9	18.919905	-5.6508736	2.4437354	2.5766079	-0.729
Nsga2_02_des0029	-4.2803845	9	17.835325	6.2243076	1.89084	3.7908583	-0.712
Nsga2_02_des0030	-4.2666514	9	19.01561	-5.7289998	1.6042206	2.4900572	-0.713
Nsga2_02_des0031	8.0382238	9	18.919905	-5.807126	2.6112657	2.5767773	-0.736
Nsga2_02_des0032	6.9697871	9	18.919905	-5.6508736	3.1398398	2.5767773	nan
Nsga2_02_des0033	-8.6612497	9	19.036973	4.1930266	1.5814603	3.615555	-0.7
Nsga2_02_des0034	8.0382238	9	18.919905	-5.6508736	2.6112657	2.5747448	-0.731
Nsga2_02_des0035	6.9835203	9	18.919905	-5.807126	2.4437354	2.5772854	-0.726
Nsga2_02_des0036	8.3897917	9	18.919905	-5.6508736	2.6112657	2.5767773	-0.709
Nsga2_02_des0037	6.6319524	9	18.919905	-5.8461891	2.4437354	2.5766079	-0.73
Nsga2_02_des0038	-3.2119478	9	18.974594	-5.6508736	2.4050629	2.5767773	-0.721
Nsga2_02_des0039	6.9835203	9	15.24126	-5.8852522	1.8136965	2.5767773	-0.723

-5.4830243 (r4, c3)

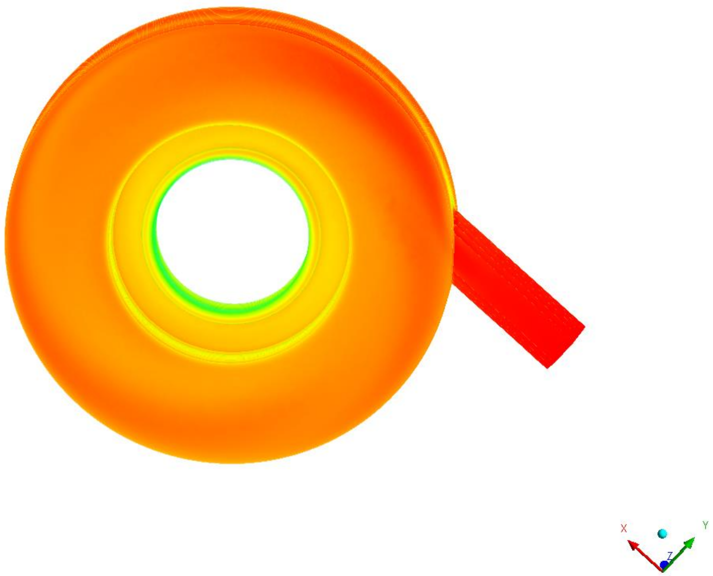
优化结果

入口切向角度　截面形状　入口轴向角度　进口管扩张度　入口轴向位置

	入口切向角度	截面形状	入口轴向角度	进口管扩张度	入口轴向位置	总压损失
优化前	40	9	0	1	2.45	9.8%
优化后	8.04	18.92	-5.65	2.61	2.57	1.1%

优化结果

进气蜗壳形状优化后总压损失显著减小。



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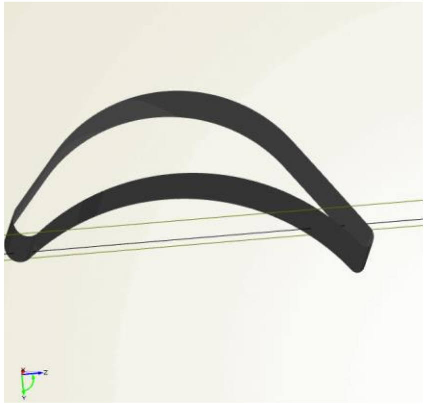
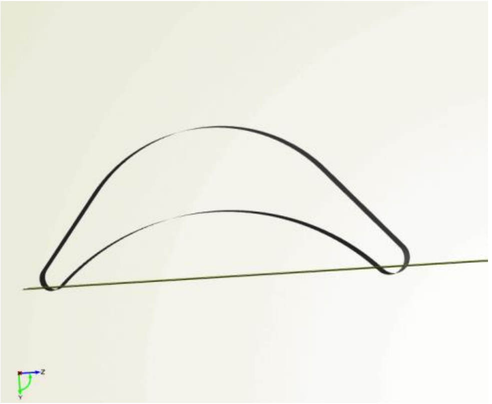
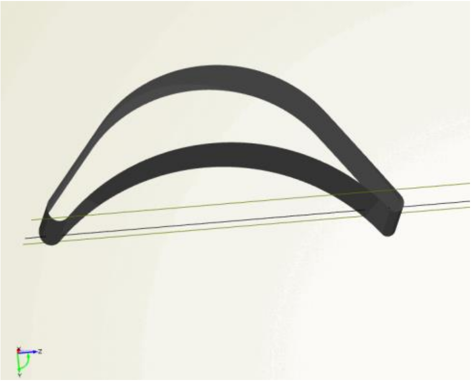
叶轮型面优化参数



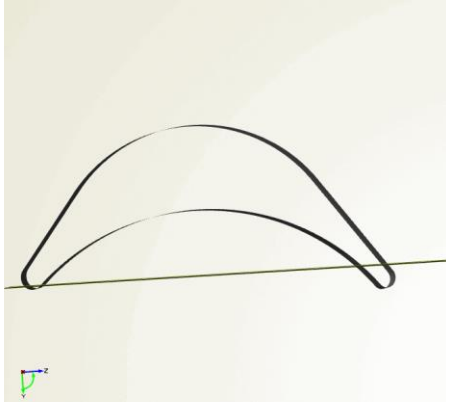
进口型线控制角1



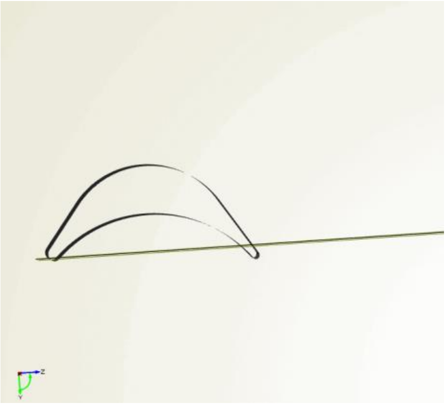
出口型线控制角1



进口型线控制角2



出口型线控制角2



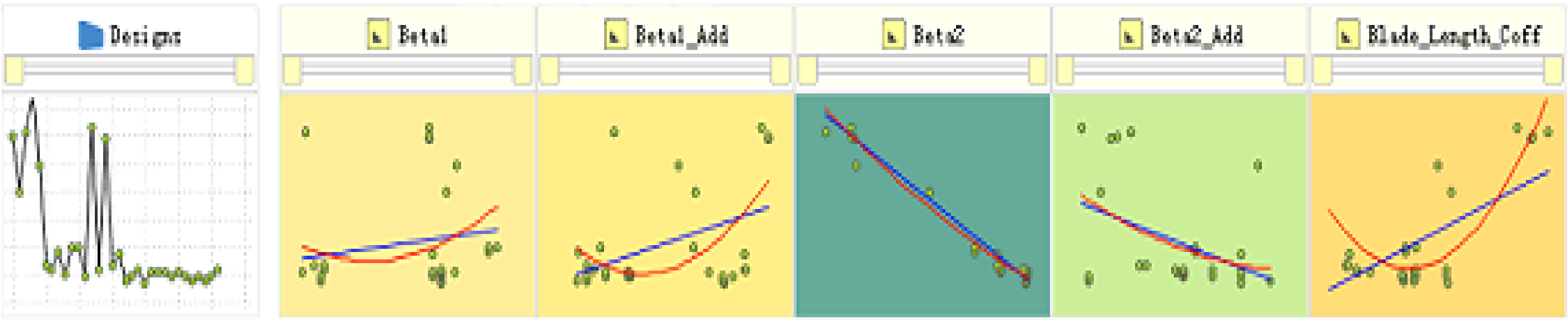
弦长系数

优化方法

- 利用CASES软件，采用遗传算法进行优化，经过5代优化，每代8个。采用8核计算平台，耗时20小时。

	Beta1	Beta1_Add	Beta2	Beta2_Add	Blade_Length_Coff	eval_eff
Mega2_04_des0020	43.105809	13.294035	51.234684	8.1335164	0.14165713	-0.747
Mega2_04_des0017	39.060746	9.1884031	51.224002	2.0790417	-0.30315062	-0.746
Mega2_04_des0027	39.060746	8.8807813	51.224002	2.002948	-0.30315062	-0.746
Mega2_04_des0029	43.105809	13.253619	51.235294	9.1335317	-0.42078279	-0.745
Mega2_04_des0011	42.904555	13.255421	51.243229	8.1335164	-0.28022431	-0.743
Mega2_04_des0024	39.072465	9.1884031	51.233768	2.0790417	-0.43829252	-0.743
Mega2_04_des0028	43.185626	10.506157	51.224918	6.1332418	0.12407874	-0.743
Mega2_04_des0030	**43.185626**	**9.754192**	**51.224918**	**8.133272**	**-0.42085145**	**-0.743**
Mega2_04_des0018	43.185626	10.410452	51.224918	7.133257	-0.43842985	-0.742
Mega2_04_des0026	42.904555	13.56347	51.243229	8.1296101	-0.28022431	-0.742
Mega2_04_des0008	43.197345	10.451469	51.234684	6.1332418	-0.43842985	-0.741
Mega2_04_des0021	42.916091	10.412161	51.243229	6.1332418	-0.88031128	-0.739
Mega2_04_des0022	38.404488	9.7597946	49.446021	5.8871443	-1.0271687	-0.739
Mega2_04_des0023	43.672145	12.879438	51.225528	8.1257038	-0.28571756	-0.739
Mega2_04_des0025	43.185626	10.451469	51.224918	6.1332418	-0.30329595	-0.739
Mega2_04_des0006	43.185809	13.911681	51.223697	6.1334859	-0.28352028	-0.738
Mega2_04_des0019	43.197528	13.952697	51.233463	6.1334859	-0.28352028	-0.738
Mega2_04_des0013	39.172076	9.3798123	49.428321	5.8790875	-1.0326619	-0.737
Mega2_04_des0005	39.172076	9.1884031	49.428321	4.6207875	-1.1732891	-0.734
Mega2_04_des0015	38.79707	9.1884031	49.193942	4.8790123	-1.1469215	-0.734
Mega2_04_des0016	42.922133	13.911681	49.193837	8.1335164	-1.1272831	-0.727
Mega2_04_des0007	44.829938	8.9201953	47.719005	6.5348151	-0.40327308	-0.724
Mega2_04_des0009	44.830121	12.380407	47.708019	6.5348592	-0.28352028	-0.722
Mega2_04_des0010	45.111192	9.5784553	47.699474	6.5348151	-0.40658901	-0.722
Mega2_04_des0001	43.348043	12.453895	44.541181	3.2914015	0.19137102	-0.681
Mega2_04_des0004	43.736233	11.913954	39.516976	8.7310597	0.0084758526	-0.662
Mega2_04_des0014	42.776013	14.62797	39.428168	3.6206302	1.2206683	-0.643
Mega2_04_des0000	42.776013	14.62797	39.19379	3.8799349	1.2470359	-0.641
Mega2_04_des0002	38.510506	9.9717708	37.370842	4.3613642	1.434287	-0.637
Mega2_04_des0012	42.776013	14.436561	39.115863	2.6206149	1.0360952	-0.634
Mega2_04_des0003	44.976791	14.507378	39.114748	4.9811246	-1.3972076	-0.608
Mega2_04_des0031	43.185809	13.951095	50.922179	7.1335012	0.12407874	pending ...

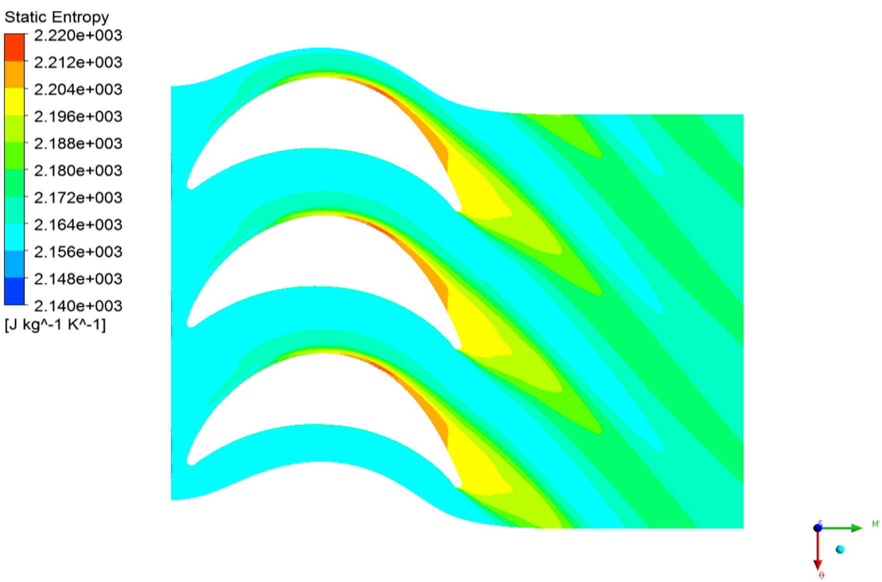
优化结果



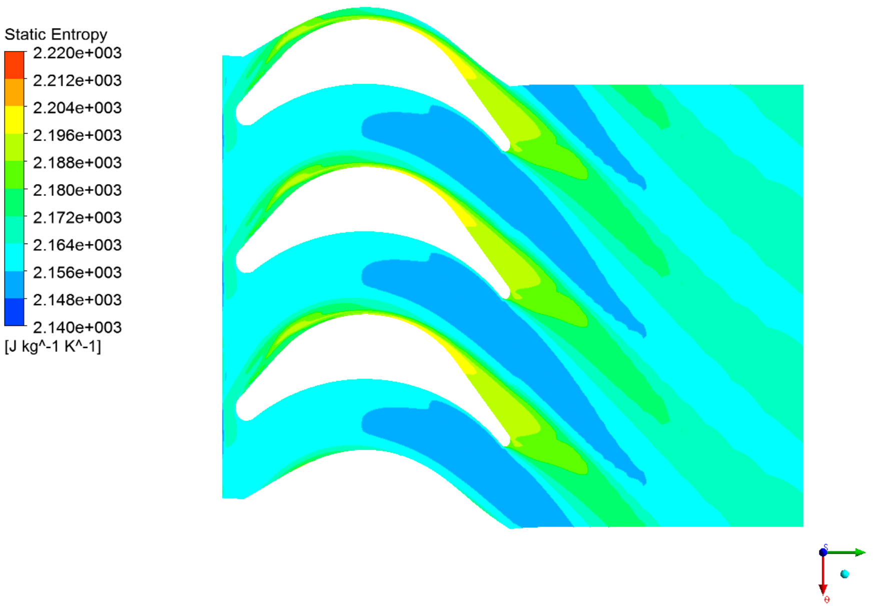
	进口型线控制角1	进口型线控制角2	出口型线控制角1	出口型线控制角2	弦长系数	效率
优化前	42	20	52	6	-0.55	73.6%
优化后	38	8.1	51.2	2.07	-0.3	74.6%

优化结果

优化后叶片吸力面流动损失显著减小。



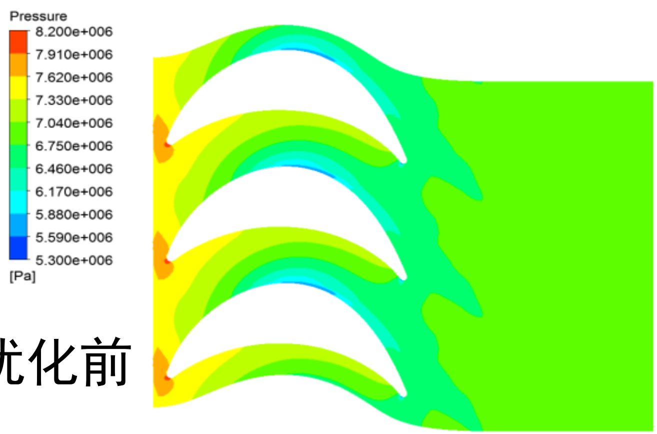
优化前



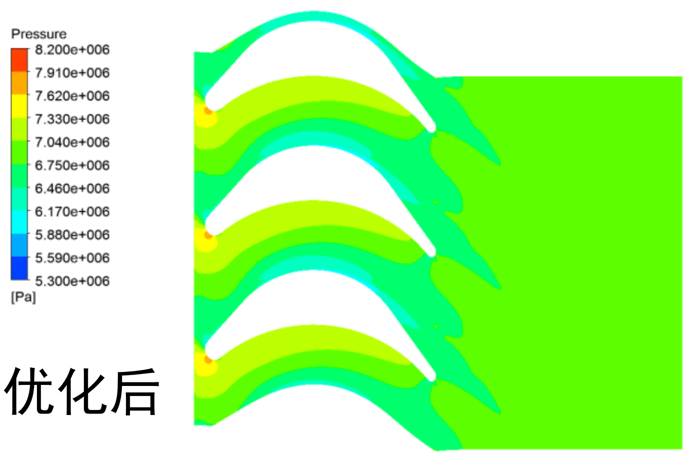
优化后

优化结果

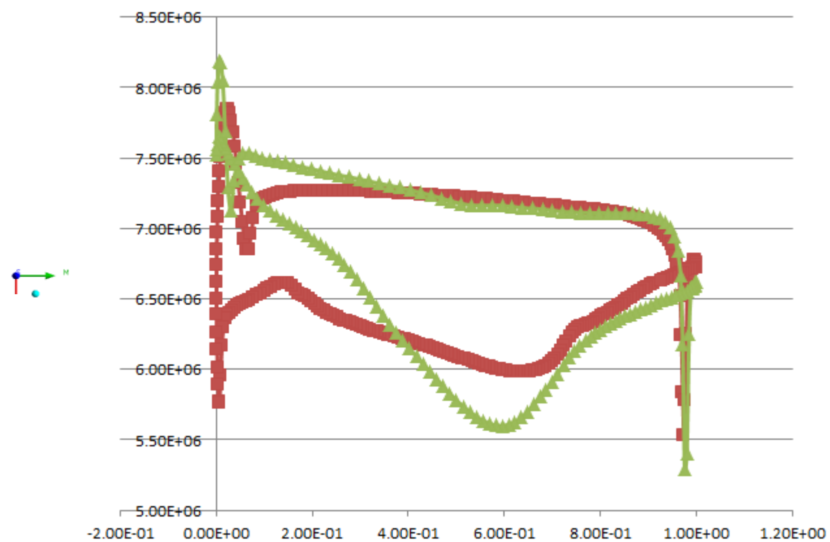
优化后叶片压力面和吸力面最大压差减小，泄漏流动降低。



优化前



优化后

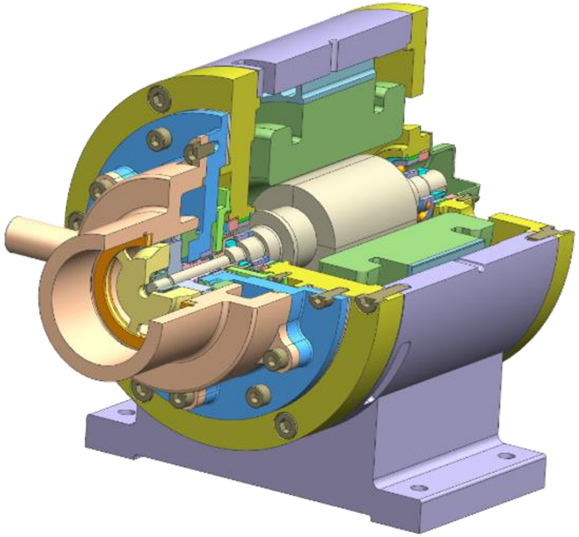


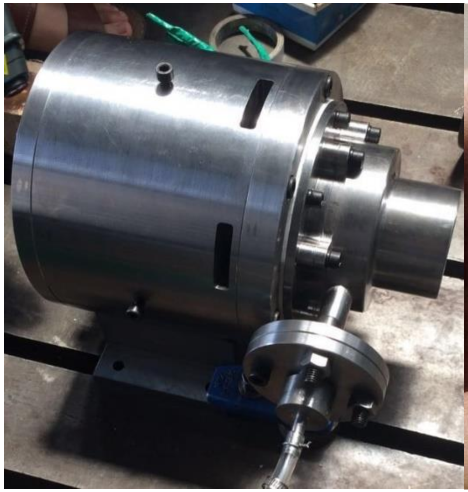
叶片表面压力分布对比

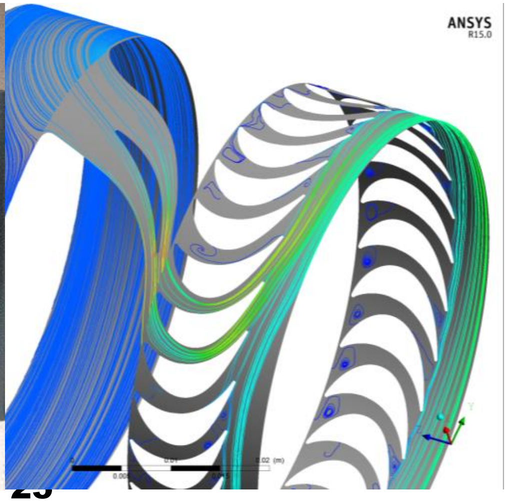
超临界CO_2涡轮膨胀机研制

主要参数

- 功率：4.5 kW（可扩展至100kW）
- 转速：40000 r/min
- 膨胀比：1.67
- 流量：0.18 kg/s







谢　谢！

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