哈爾濱工程大學
Harbin Engineering University

基于引射器实现天然气发动机高EGR率的研究

Research on realizing high-EGR rate of natural gas engine based on ejector

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汇报目录 Catalogue

一、研究背景

Research background

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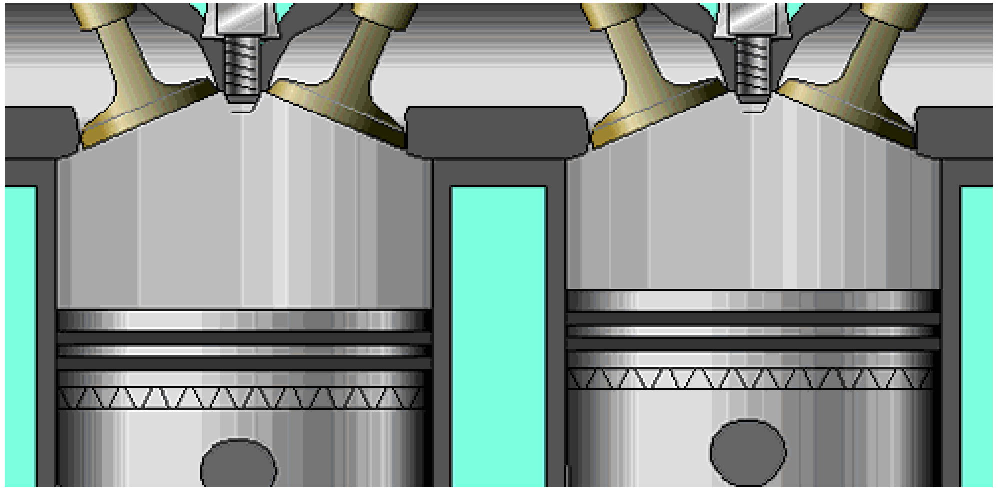
排放清洁
Clean emissions

经济效益高
High economic benefit

储量丰富
Rich reserves

天然气发动机
Natural gas engine

爆 震
Engine knock

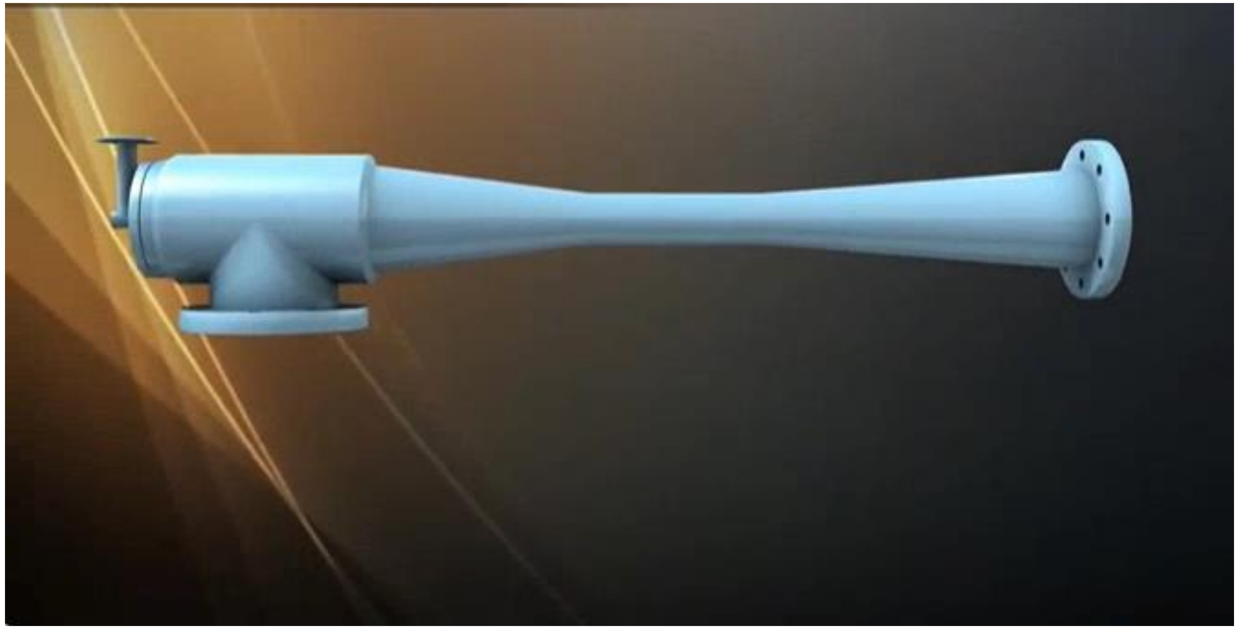


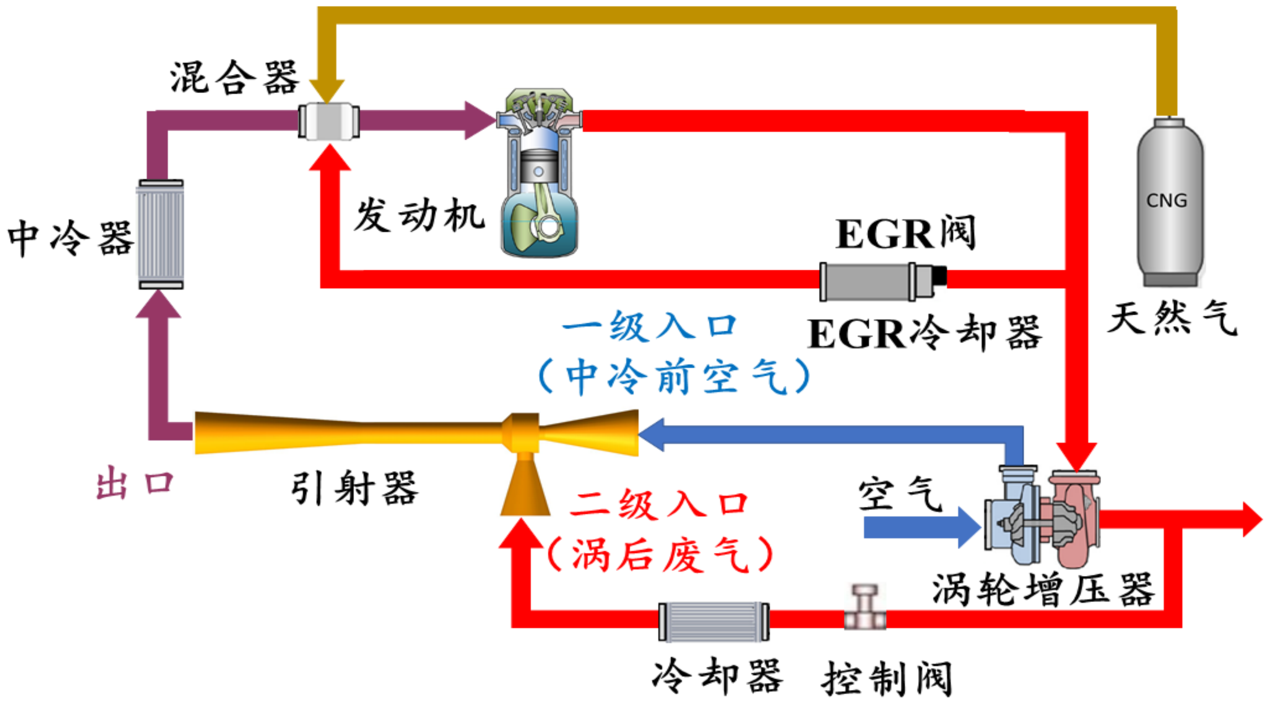
对于火花塞点火式天然气发动机，EGR可以降低缸内热负荷，在一定程度实现抑制爆震，但这对于大负荷工况却存在问题。

For spark ignition natural gas engines, EGR can reduce the thermal load in the cylinder to suppress knocking, but this solution still has some problems when the engine is under heavy load conditions.

涡轮增压和高EGR率“鱼与熊掌”无法兼得。

It is difficult to achieve turbocharging and high-EGR rate at the same time





引射器能够无功耗实现高压气体和低压气体的混合，根据其特性提出右图所示的天然气发动机高EGR率方案，在不影响涡轮增压效果下达到增加发动机气缸内废气量的目的。

The ejector can mix the high-pressure gas and low-pressure gas without power. The picture shows the high-EGR rate scheme of natural gas engine based on ejector, which can increase the exhaust gas volume in the engine cylinder without affecting the turbocharging.

一、研究背景
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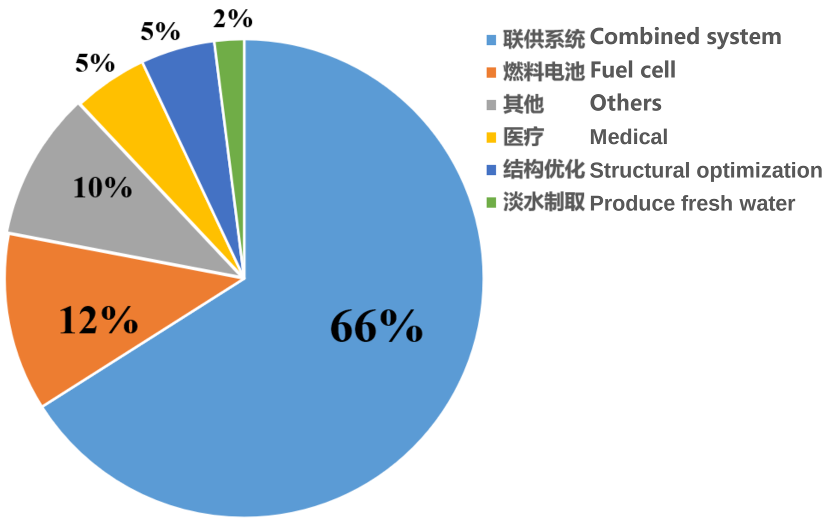
哈尔滨工程大学
Harbin Engineering University

引射器SCI文章发表数
The number of published SCI articles related to ejector

发表年限 Years of publication	文章数量 Number of articles
2020	310
2021	386
2022	361
2323	39



被引量前100文章研究领域
The research fields of the top 100 cited articles

调研发现在已发表的引射器SCI文献中存在以下问题：
Through research, it is found that the following problems exist in the published SCI literature of ejectors:

- **大部分文献直接使用现有的引射器结构参数，而未说明引射器结构参数的设计过程**
  Most of the literature directly uses the existing ejector structural parameters, but does not explain the design process of the ejector structural parameters
- **在引射器的设计方法中，多数文献均是基于双拥塞假设来进行结构设计，设计工况受限**
  Many of the ejector design methods in the literature are based on the double congestion assumption for structural design, so the design conditions are limited
- **提出的设计方法仅适用于引射器处于超临界或亚临界条件下，不具有普适性**
  The proposed design method is only suitable for ejectors under supercritical or subcritical conditions, so it is not universal

亟需提出一种详细且普适性强的引射器正向设计方法
It is urgent to propose a detailed and universal ejector structural design method

二、引射器正向设计方法

Forward design method of ejector

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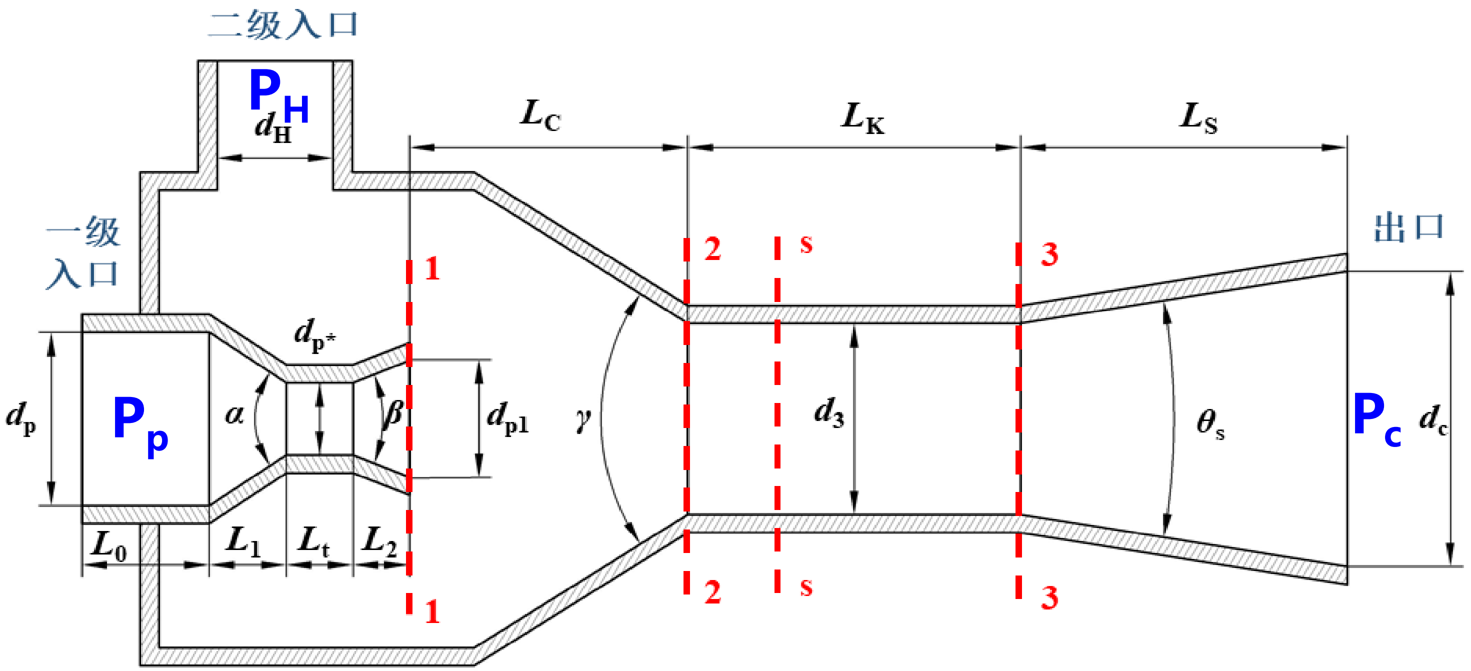
Forward design method of ejector

引射器结构示意图 Design method flow of ejector

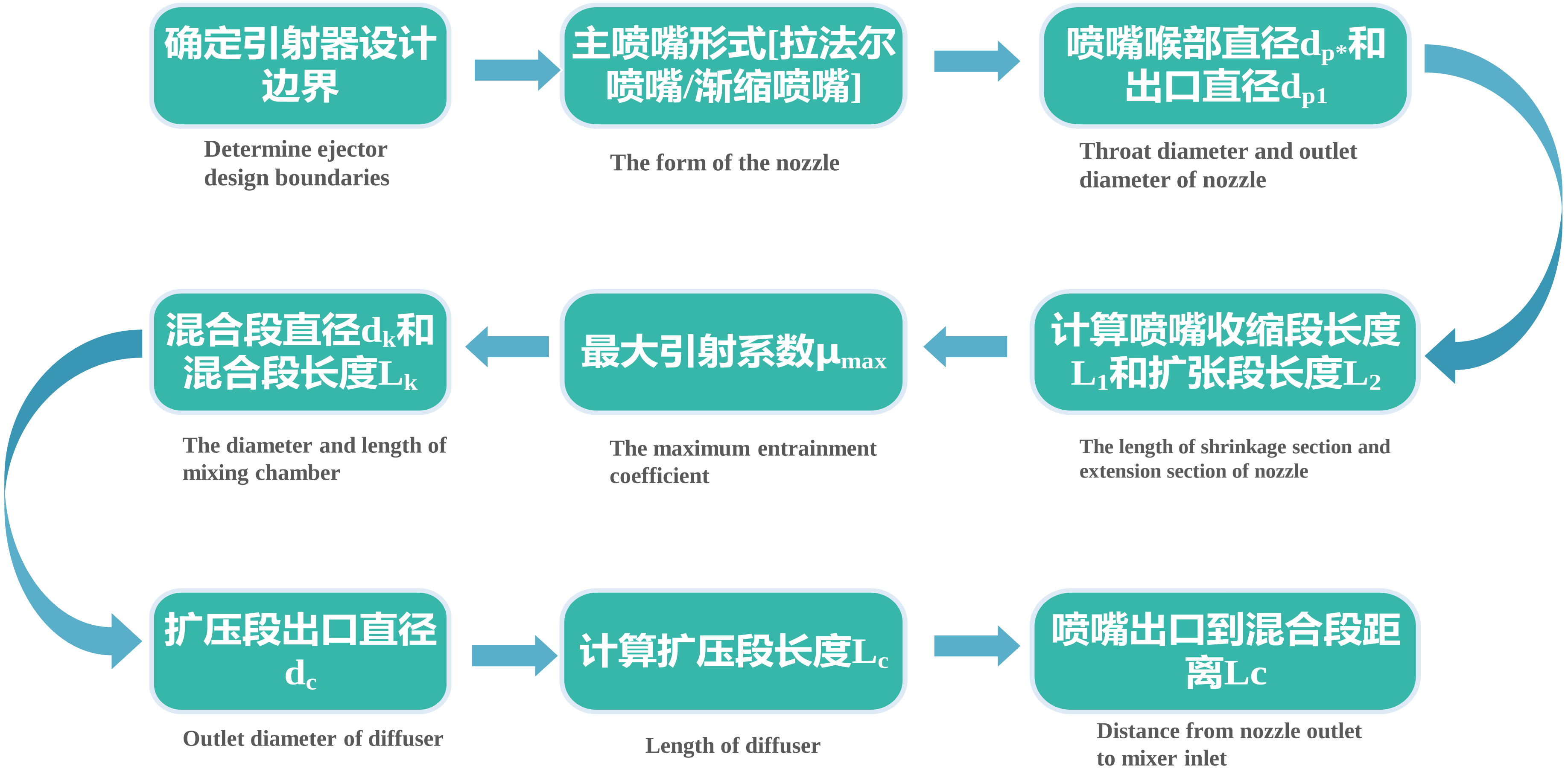


截面1-1：喷嘴出口处；截面2-2：混合段入口处；截面3-3：扩压段入口处

section 1-1: exit of nozzle; section 2-2: entrance of mixing chamber; section 3-3: entrance of diffuser

符号符	含义
d_p	喷嘴入口直径 / Inlet diameter of nozzle
d_{p*}	喷嘴临界直径 / Critical diameter of the nozzle
d_{p1}	喷嘴出口直径 / Outlet diameter of nozzle
d_h	二级入口直径 / Inlet diameter of secondary flow
d_3	等容混合器直径 / Diameter of mixing chamber
d_c	扩压段出口直径 / Outlet diameter of diffuser
L_0	喷嘴入口段长度 / Inlet length of nozzle
L_1	喷嘴收缩段长度 / Shrinkage section length of nozzle
L_t	喷嘴喉部长度 / Length of nozzle throat
L_2	喷嘴扩张段长度 / Length of nozzle extension
L_C	喷嘴出口到混合器入口的距离 Distance from nozzle outlet to mixer inlet
L_K	混合段长度 / Length of mixing chamber
L_S	扩压段长度 / Length of diffuser
α	喷嘴收缩角 / Contraction angle of nozzle
β	喷嘴扩散角 / Divergence angle of nozzle
γ	接收段夹角 / Angle of receiving section
θs	扩压段扩散角 / Diffusion angle of diffuser

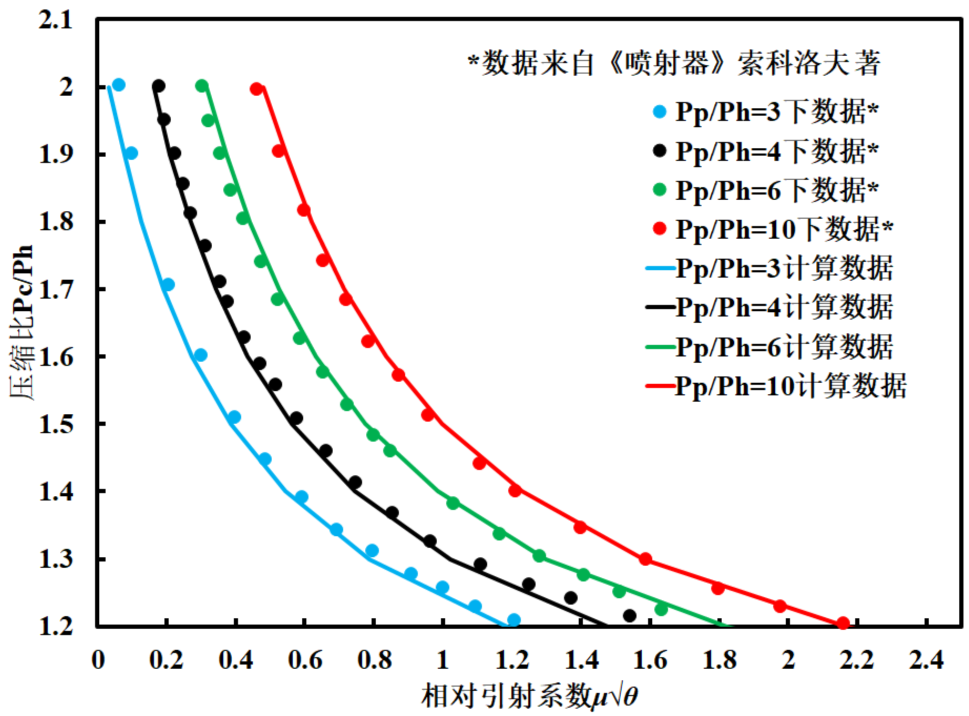
引射器设计方法流程 Design method flow of ejector

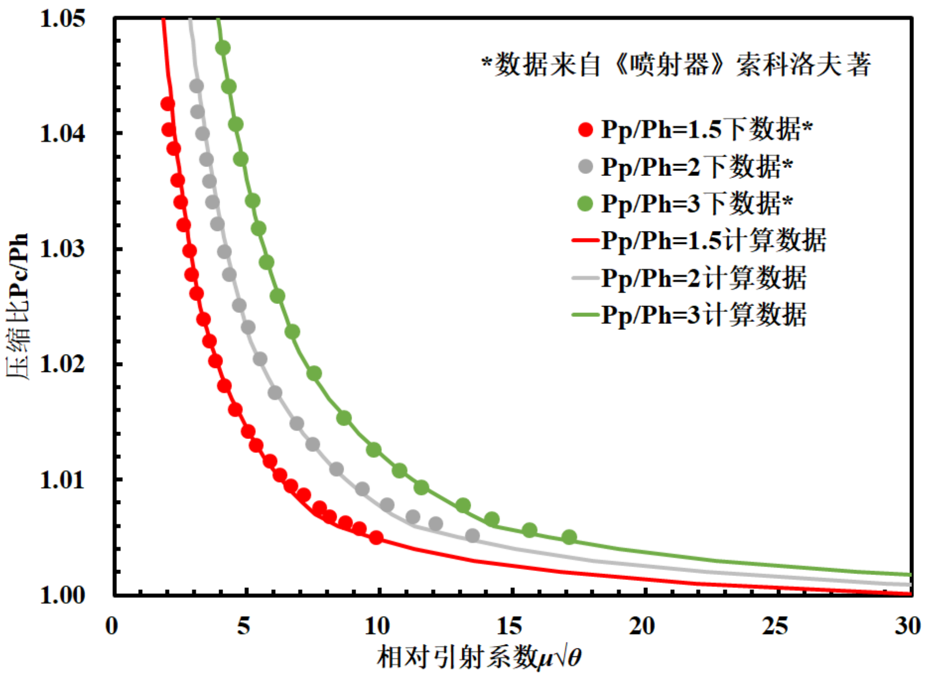


二、引射器正向设计方法

Forward design method of ejector

最大引射系数对比 Comparision of maximum entrainment coefficient





在不同的压缩比和膨胀比下，本项目编写的程序的计算结果和实验数据具有非常好的吻合性。证明所开发的程序的准确性。

Under different compression ratio and expansion ratio, the calculated results of the program written in this project have a very good agreement with the experimental data. Demonstrate the accuracy of the developed program

三、基于引射器的发动机高EGR率技术方案

High-EGR rate technical scheme for engines based on ejector

哈爾濱工程大學
Harbin Engineering University

发动机高EGR率方案研究 Research on high-EGR rate scheme of engine-Scheme

引射器实现20%EGR率下的引射系数=0.25。

To achieve a 20% EGR rate, the entrainment coefficient needs to reach 0.25.

涡前废气排压 Exhaust gas pressure before turbine	kPa	292.9	268.6
中冷前气压 Pressure before intercooler	kPa	241.5	266.1

一级气体的压力（P_p=266.1 kPa）是确定的，但是二级气体的压力P_H、引射器出口背压P_c是不确定的。

The pressure of the primary gas (P_p=266.1 kPa) is determined, but the pressure P_H of the secondary gas and the back pressure P_c of the ejector outlet are uncertain.

潍柴给出了三个压力边界之间的压损关系建议：

Weichai gives suggestions on the pressure loss relationship between the three pressure boundaries:

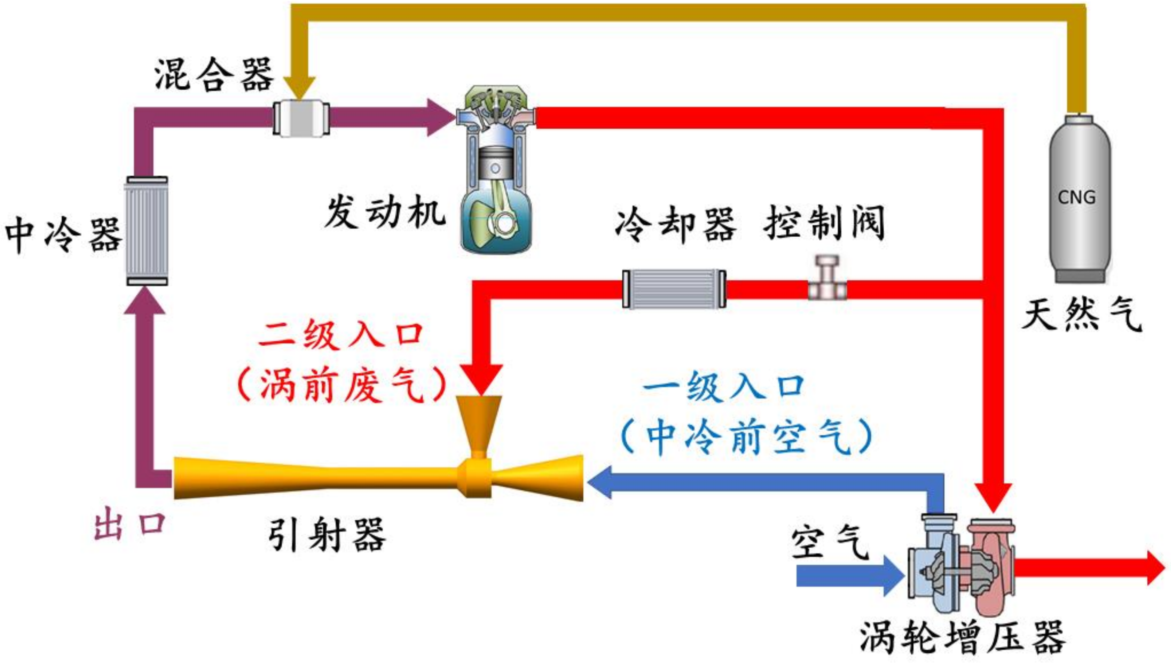
P_p-P_c在20~40 kPa范围内；

Pp-Pc in the range of 20~40 kPa

P_H比涡前压力小30～40 kPa。

PH is 30-40 kPa smaller than the pre-vortex pressure.

P_c=226.1~246.1 kPa，P_H=228.6~238.6 kPa。



四、引射器结构参数优化方法

Optimization method of ejector structural parameters

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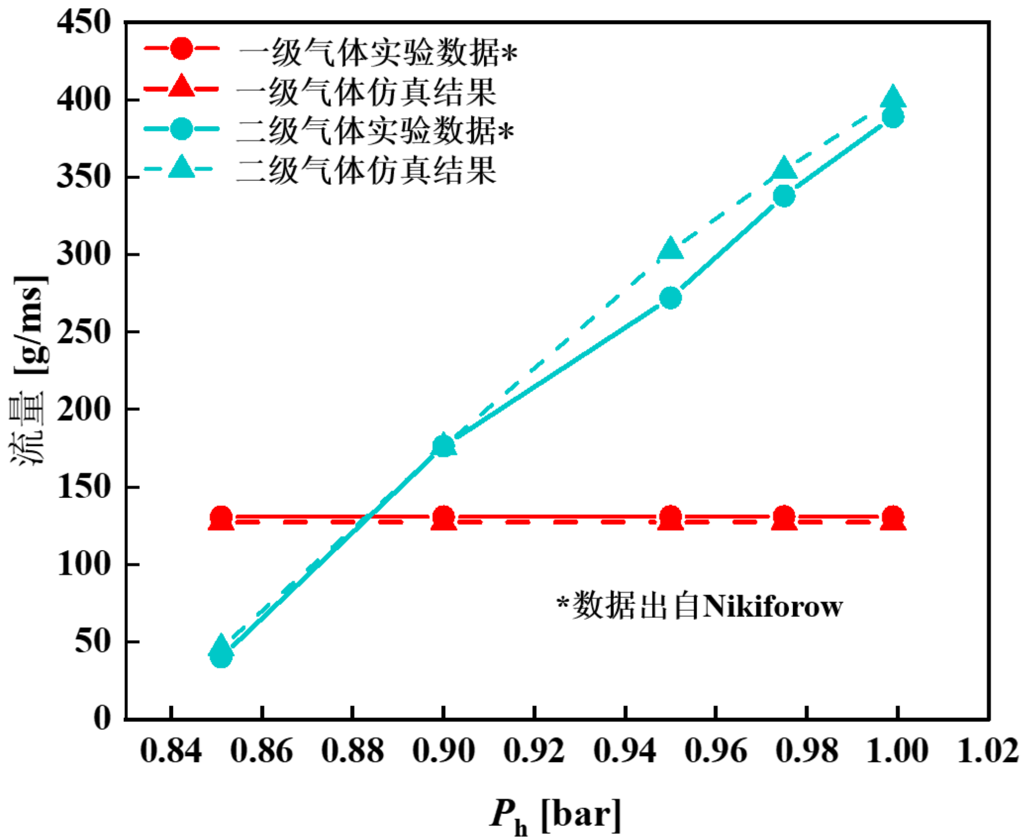
Optimization method of ejector structural parameters

引射器仿真研究-仿真计算结果对比验证 Comparison and verification of simulation calculation results



为了验证仿真模拟结果的准确性，流量仿真结果与Nikiforow*的5组不同压力边界下试验数据进行对比，对比结果如图所示；

In order to verify the accuracy of the simulation results, under the five different sets of pressure boundaries shown in the above table, the flow simulation calculation results are compared with the experimental data, and the comparison results are shown in the figure;

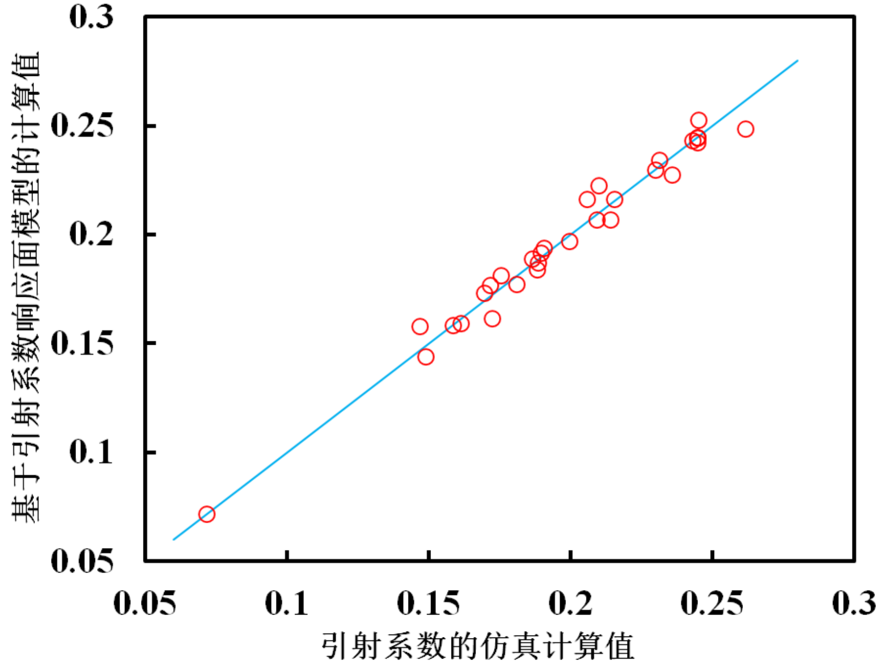
从图中看到一级流量和二级流量的计算结果和实验数据具有较好的吻合性，误差均低于10%，满足工程研究误差要求，证明了本文采用的引射器模型能够准确的模拟引射器的工作过程。

It can be seen the calculation results is in good agreement with the experimental data, and the errors are all less than 10%, which meets the error requirements of engineering research and proves that the ejector model used in this paper can accurately simulate the working process of the ejector.

*NIKIFOROW K, KOSKI P, KARIMAKI H, et al. Designing a hydrogen gas ejector for 5 kW stationary PEMFC system- CFD-modeling and experimental validation[J]. International Journal of Hydrogen Energy,2016,41(33): 14952-14970.

引射系数响应面模型 Entrainment coefficient response surface model

结构参 / Parameters	符号 / Symbol	取值范围 / Ranges
d_3 (mm)	x_1	40.1～48.1
L_S (mm)	x_2	265～365
L_K (mm)	x_3	85～265
θ_S (°)	x_4	4～12
L_C (mm)	x_5	35～75



引射系数响应面模型

Entrainment coefficient response surface model

$$
\begin{aligned}
y = {} & f(x_1, x_2, x_3, x_4, x_5) \\
= {} & -2.6781 + 0.1270x_1 + 0.0019x_2 - 0.0018x_3 + 0.0033x_4 \\
& - 0.0022x_5 - 0.0017x_1^2 - 1.9619\times10^{-6}x_2^2 - 1.3098\times10^{-6}x_3^2 \\
& - 0.0012x_4^2 - 2.5712\times10^{-5}x_5^2 + 5.0019\times10^{-6}x_1x_2 \\
& + 5.8243\times10^{-5}x_1x_3 + 2.4716\times10^{-4}x_1x_4 + 1.7910\times10^{-4}x_1x_5 \\
& - 1.2816\times10^{-7}x_2x_3 - 1.4663\times10^{-5}x_2x_4 - 7.1471\times10^{-4}x_2x_5 \\
& + 3.6145\times10^{-5}x_3x_4 - 5.3885\times10^{-6}x_3x_4 + 3.9141\times10^{-5}x_4x_5
\end{aligned}
$$

基于响应面的预测值集中分布在蓝色回归线附近，证明响应模型计算的准确性。

The predicted resulet proves that the response model calculation is accurate.

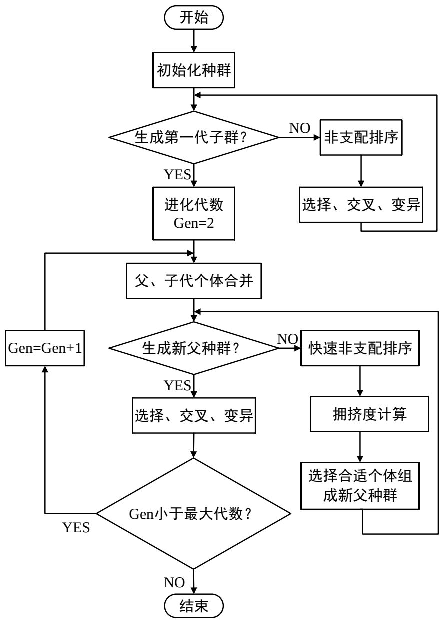
四、引射器结构参数优化方法

Optimization method of ejector structural parameters

引射器尺寸优化方法及结果 Optimization method and results of structural parameters of ejector

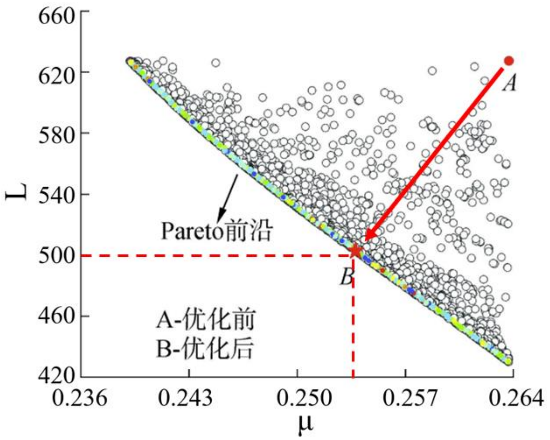
非支配遗传算法的种群根据个体之间的支配与非支配关系进行排序，并采用帕累托最优策略，求解出多个优化目标下的最优解，以最大引射系数μ和最小引射器长度L为多优化目标，进行几何参数的多参数协同优化。

The non-dominated genetic algorithm adopts the pareto optimal strategy, which could solve the optimal solution of the problem of multiple optimization objectives. Therefore, the maximum entrainment coefficient μ and the minimum ejector length L are jointly used as the multiple optimization objectives, and the multi-optimization of geometric parameters is carried out.



非支配遗传算法计算流程图
Calculation flow chart of non-dominated genetic algorithm

$$
\begin{cases}
\max \mu = f(x_1, x_2, x_3, x_4, x_5) \\
\min L = f(x_2 + x_3 + x_5) \\
x_{i\min} \le x_i \le x_{i\max}, (i = 1, 2, \ldots, 5) \\
\mu \ge 0.25 \\
L \le 500
\end{cases}
$$



参数 Paramters	优化前 Before optimization	优化后 After optimization	变化量 Variables
x_1 [mm]	44.1	41.7	-2.4
x_2 [mm]	315	358	+43
x_3 [mm]	265	102	-163
x_4 [°]	8	5.6	-2.4
x_5 [mm]	51	40	-11
L[mm]	631	500	-131
μ	0.2637	0.2548	-0.0089
EGR率	20.9%	20.3%	-0.6%

- **经过优化后，μ虽然略微减小，但仍然满足设计的要求，μ>0.25**
  After optimization，although μ is slightly reduced, it still meets the design requirements，μ>0.25
- **经过优化后，轴向长度从631mm减小到500mm，减小近21%**
  After optimization, the axial length is reduced from 631mm to 500mm, a reduction of nearly 21%

五、引射器的性能试验验证

Experimental verification of ejector performance

五、引射器性能试验验证

Experimental verification of ejector performance

哈爾濱工程大學
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引射器试验设备及边界条件 Experimental equipment and boundary conditions

组数 Group	一级压力 [bar] Primary pressure	二级压力 [bar] Secodnary pressure	背压 [bar] Back pressure
1	1.2	1	1
2	1.4	1	1
3	1.6	1	1
4	1.8	1	1
5	2	1	1

空压机
Air compressor

气体测量范围：86~1100m³/h
Gas measurement range
输出频率范围：55~690Hz
Output frequency range

大流量涡街流量计
Large flow vortex flowmeter

容积：1m³
Volume
压力：0.8MPa
Pressure

稳压储气罐
Gas tank

引射器试验台 Testbed of ejector

引射器测试试验台
The testbed of ejector

衷心感谢内燃机可靠性国家重点实验室开放课题的资助！

Thank the state key laboratory of internal combustion engine reliability for funding the open project sincerely!