CFD and experimental studies on the hydrodynamic performance of submerged flat-sheet membrane bioreactor equipped with micro-channel turbulence promoters

Fang Xie, Weiwei Chen, Jianmin Wang, Jinrong Liu*

School of Chemical Engineering, Inner Mongolia University of Technology, Hohhot 010051, PR China

A R T I C L E   I N F O

Article history:
Received 15 March 2015
Received in revised form 18 August 2015
Accepted 11 October 2015
Available online 22 October 2015

Keywords:
Computational fluid dynamics
Submerged flat-sheet membrane bioreactor
Micro-channel turbulence promoters
Membrane fouling
Flux enhancement

A B S T R A C T

The aim of the present work is to propose a new type of micro-channel turbulence promoters equipped with the submerged flat-sheet membrane bioreactor to enhance membrane flux, mitigate membrane fouling and reduce energy consumption. The hydrodynamic and filtration performance of micro-channel turbulence promoter (MCTP) with micro-pores and without micro-pore in the submerged flat-sheet membrane bioreactor carried out by computational fluid dynamics (CFD) simulations and filtration performance experiments. The CFD simulation results and the experimental results showed that MCTP with micro-pores in the submerged flat-sheet membrane bioreactor could further increase average velocity 10.41%, turbulent kinetic energy 4.41% and wall shear stress 56.00% on the flat-sheet membrane surface, thereby enhancing membrane flux 21.64%, decrease total resistance 46.41% and save energy 28.76% compared with MCTP without micro-pore.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

The submerged membrane bioreactor (SMBR) has been widely used in municipal and industrial wastewater treatment field. But the rapid decreasing flux and serious membrane fouling are the major obstacles for more widespread application [1,2]. At present, the use of turbulence promoters (TP) is one of the most popular solutions under study in reducing permeate flux decline and controlling membrane fouling [3–5]. Different configurations of turbulence promoters including Kenics static mixers [6,7], cylindrical wire-promoters [8,9], twisted tapes [10], helical screw inserts [11], cylindrical inserts, helical inserts and winding inserts [12,13], baffles [14], spacers [15] and cross-section inserts [16] are extensively used to improve the flux and filter performance of the tubular membrane in treating wastewater.

Li et al. [17] compared the effects of promoter geometry on flow pattern by numerically simulation. It was obtained that the turbulence promoter increased the flow instability, the recirculation occurred in the presence of the turbulence promoter. Ghidossi et al. [18] gave a review on CFD simulations of hydrodynamics for microfiltration, ultrafiltration or nanofiltration processes with the introduction of pulsatile flow and gas sparging, spacers, Dean and Taylor vortices and geometry. Ahmed et al. [19] presented CFD simulation of turbulence promoters in tubular membrane channel and validated CFD simulation result by performing crossflow microfiltration of titanium dioxide suspension experiment. It was shown that turbulence promoter can improve the local shear stress on the membrane surface and produce eddy activities which enhance the filtration performance. Liu et al. [20] documented that the presence of baffles caused remarkable increase of the average velocity and shear stress on the tube wall by CFD simulations and crossflow microfiltration of calcium carbonate suspensions experiment. Bellhouse et al. [21] investigated the detailed fluid dynamic processes contributing to flux enhancement of tubular membranes by screw thread inserts and optimized the geometry of the inserts. Wu et al. [22] indicated that micromixing efficiency in a ceramic membrane reactor was intensified using turbulence promoter. The results showed that the turbulence promoter can further intensify the micro-mixing efficiency of the reactor in a sequence of entry tube < cylindrical insert < helical insert < Kenics™ static mixer insert. Ahmad et al. [23] studied the effect of applying reciproca- tion movement to channel filled with a corrugated spacer using CFD. The results showed that the average shear stress on the membrane was found to increase exponentially with the membrane velocity which changed sinusoidally as a function of time and the motor rotation speed. Liu et al. [24] established artificial neural network model for the turbulence promoter-assisted crossflow microfiltration process and provided a useful
guide for the application of turbulence promoter in crossflow microfiltration processed.

According to previous work, turbulence promoters can enhance membrane filtration performance and reduce the membrane fouling. Moreover, now the enhancement effect of turbulence promoters on MBR, both CFD simulation and filtration performance experiments were mainly concentrated on the tubular membrane bioreactor, while, on the other hand, almost no investigations deal with flat-sheet membrane bioreactor. In the case of flat-sheet membrane bioreactor, on the basis of the previous studies, Winzeler and Belfort [3] and Li et al. [17] suggested that the most common turbulence promoter was directly placed on the membrane surface, however, in such manner that the effective membrane area reduces, and the axial pressure drop and energy consumption increase.

The purpose of the present work is to propose a new type of MCTP with micro-pores equipped with the submerged flat-sheet membrane bioreactor to increase the effective membrane area, improve the filter flux, mitigate membrane fouling and reduce energy consumption. The flux enhancement using turbulence promoter depends on the improved hydrodynamic characteristics on the membrane surface. CFD is used to simulate the hydrodynamic performance in the flat-sheet membrane bioreactor equipped MCTP with micro-pores and MCTP without micro-pore, then the filtration performance and membrane fouling resistance experiment of flat-sheet membrane bioreactor are conducted to validate the enhancement effect of micro-channel turbulence promoters on SMBR performance.

2. CFD model and numerical method

2.1. Model geometry and meshing

The 2D computational flow domain of the rectangle flat-sheet membrane channel with a width of 72 mm and length of 320 mm is shown in Fig. 1. As illustrated in Fig. 1, the corrugated MCTP was crosswise placed on the membrane surface. The schematic diagram of corrugated micro-channel turbulence promoters without and with micro-pores is illustrated in Fig. 2. There are micro-channels among corrugated protrusions on the turbulence promoter surface. The size of micro-channel, wave height, wave length and micro-pore diameter is 1 mm, 2 mm, 4 mm and 0.3 mm, respectively. The channel geometry was conducted using Meshing of ANSYS 13.0, and was discretized to a sufficiently large number of 126, 417 cells to obtain a grid independent solution. The element and grid type were quad and pave. The finer computational grids were employed in the MCTP by defining the fixed size function, where high gradients of velocity and shear stress may exist [19].

![Fig. 1. Schematic diagram of flat-sheet membrane with MCTP positions.](image)

2.2. Turbulence model

The standard k-epsilon model is used to implement CFD simulations. It is assumed that the fluid is incompressible, with constant physical properties and steady turbulent state flow. Under these assumptions, in the standard k-epsilon model, turbulent kinetic energy (k) and turbulent dissipation rate (ε) are the two basic unknown quantities, whose transport equations are as follows [25]

\[ \frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} + G_k - \rho \varepsilon \]  

(1)

\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \mu + \frac{\mu_t}{\sigma_{\varepsilon}} \right) \frac{\partial \varepsilon}{\partial x_i} + C_1 \frac{\varepsilon}{k} G_k - C_2 \rho \varepsilon^2 \]  

(2)

where \( \mu \) (kg/m s) is the density, \( u \) the velocity (m/s), \( P \) the pressure (Pa), \( \mu \) the viscosity (Pa s), \( G_k \) the turbulent kinetic energy caused by the average velocity gradient, \( C_{1 \varepsilon} = 1.44, C_{2 \varepsilon} = 1.92, \delta_1 = 1.0, \) and \( \delta_2 = 1.3. \)

The standard wall functions are expressed as

\[ G_k \approx r_w \frac{\partial u}{\partial y} \approx r_w \frac{C_\mu}{k \rho^{3/4} \nu_{sf}^{1/2}} \Delta y_p \]  

(5)

\[ \varepsilon = \frac{C_\mu}{k} \frac{\nu_{sf}^{3/2}}{\Delta y_p} \]  

(6)

where \( r_w \) is wall shear stress (Pa), \( \Delta y_p \) the distance from P point to the wall (m), \( k = 0.42, C_\mu = 0.09, \) and \( k_p \) the turbulent kinetic energy at P point (m2/s2).

2.3. Solution approach and boundary conditions

The CFD code (Fluent 13.0), which employs the finite volume method, was used to simulate the hydrodynamic characterization in the channel between micro-channel turbulence promoters and the flat-sheet membrane. The computational domain was discretized by a second order upwind differencing scheme. The pressure–velocity coupling scheme was resolved with SIMPLE algorithm. The scaled residuals were monitored to a criterion of \( 10^{-5} \) for the continuity and momentum variables as well as k-epsilon to ensure the convergence of the numerical solution. The fluid flow in the membrane channel without turbulence promoters (NTP) was also simulated for the purpose of comparison. The boundary conditions used here are identical for all cases of these simulations, with an inlet velocity of 0.5 m/s and the outlet set as outflow.

3. Experimental

3.1. Experimental setup

The filtration performance and membrane fouling resistance experiments were performed with a submerged flat-sheet membrane bioreactor. In order to conduct comparison testing,
the parallel apparatus used to treat synthetic wastewater is presented in Fig. 3. A flat-sheet microfiltration with a pore size of 0.1 µm was submerged in an aerobic bioreactor with an effective volume of 68 L at the laboratory scale. Each flat-sheet membrane made of PVDF had a filtration area of 0.1 m² with a total effective membrane area of 0.5 m². The SMBR was operated at a constant pressure. Mixed liquid suspended solids (MLSS) concentration was about 6 g/L. The influent pump was controlled by a water level sensor to maintain a constant water level in the bioreactor. The influent and effluent characteristics are shown in Table 1. The pressure drop along the membrane channel was measured with a membrane pressure gauge. The permeate fluxes of flat-sheet membrane were monitored during the entire experiment.

3.2. Experimental methods

The pressure drop of SMBR was measured with a membrane pressure gauge. The permeate fluxes of submerged flat-sheet membrane bioreactor were monitored during the whole experiment. Flux improvement (FI) efficiency, reduction of hydraulic dissipation power (PR) and reduction of specific energy consumption (ER) are defined as

\[ FI = \frac{J_{TP} - J_{NTP}}{J_{NTP}} \times 100\% \]  

\[ PR = \frac{P_{TP} - P_{NTP}}{P_{NTP}} \times 100\% \]  

\[ ER = \frac{E_{TP} - E_{NTP}}{E_{NTP}} \times 100\% \]

Table 1 Influent and effluent characteristics.

<table>
<thead>
<tr>
<th></th>
<th>COD (mg/L)</th>
<th>NH₃-N (mg/L)</th>
<th>SS (mg/L)</th>
<th>Turbidity (NTU)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>320–530</td>
<td>19–30</td>
<td>70–190</td>
<td>17–75</td>
<td>15–25</td>
</tr>
<tr>
<td>Effluent</td>
<td>≤12.57</td>
<td>≤2.58</td>
<td>0</td>
<td>≤0.27</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Schematic diagram of MCTP without and with micro-pores.

Fig. 3. Schematic of SMBR experimental setup.
\[ P = Q \times \Delta P \]  
\[ E = \frac{P}{A \times J} \] 

where \( J_{TP} \) and \( J_{NTP} \) are the permeate flux of membrane with and without turbulence promoter (L/m\(^2\) h), \( P_{TP} \) and \( P_{NTP} \) hydraulic dissipation power with and without turbulence promoter (W), \( E_{TP} \) and \( E_{NTP} \) specific energy consumption with and without turbulence promoter (kWh/m\(^3\)), \( Q \) influent rate (m\(^3\)/s), \( P \) hydraulic dissipation power (W), \( E \) specific energy consumption (kWh/m\(^3\)), and \( A \) membrane area (m\(^2\)).

The membrane fouling resistance was expressed as [26,27]
\[ R = \frac{\Delta P}{\mu J} \] 

where \( R \) is the membrane filter resistance (m\(^{-1}\)), \( \Delta P \) the pressure drop along the membrane channel (Pa), \( \mu \) the dynamic viscosity (Pa s), and \( J \) permeate flux of membrane (L/m\(^2\) h).

In the course of the experiment, the resistance can make the following decomposition:
\[ R_t = R_{in} + R_{p} + R_{c} + R_{I} + R_{d} + R_{ef} \] 

where \( R_t \) is total resistance (m\(^{-1}\)), \( R_{in} \) the intrinsic resistance of new membrane (m\(^{-1}\)), \( R_{p} \) polarization resistance (m\(^{-1}\)), \( R_{c} \) cake layer resistance (m\(^{-1}\)), \( R_{I} \) internal fouling resistance (m\(^{-1}\)), \( R_{d} \) external fouling resistance (m\(^{-1}\)).

In the following CFD simulations and filtration experiments, SMBR-A is denoted as SMBR without MCTP; SMBR-B is SMBR equipped MCTP without micro-pore, and SMBR-C is SMBR equipped MCTP with micro-pores.

4. Results and discussion

4.1. Numerical results

4.1.1. Velocity

It can be seen from Fig. 4 that the flow velocity of SMBR-C is higher than that of SMBR-B. As to SMBR-C, the rough and peak values of velocities are about 0.84 m/s and 1.24 m/s, respectively. For the SMBR-B, the peak value of wall velocity is about 1.13 m/s, and the rough value is close to 0.78 m/s. However, for the SMBR-A, the peak value of wall velocity is about 0.55 m/s and its rough value is close to 0.51 m/s. Comparing with SMBR-A, the increase rate of velocity of SMBR-B and SMBR-C is 59.40% and 69.81%, respectively. The increase rate of velocity of SMBR-C is higher than that of SMBR-B (10.41%). The high flow velocity can only increase turbulence in the bulk fluid stream but also interrupt the buildup of the boundary layer and disturb the development of the concentration polarization layer on the membrane surface, thereby reducing membrane fouling and enhancing the membrane flux.

4.1.2. Turbulent kinetic energy and turbulent intensity

It can be observed from Fig. 5 that the turbulence kinetic energy of SMBR-C is higher than that of SMBR-B. The average turbulence kinetic energy of SMBR-B and SMBR-C is 0.0259 and 0.0339 m\(^2\)/s\(^2\), respectively. Comparing with SMBR-A, the increase rate of turbulence kinetic energy of SMBR-B and SMBR-C is 81.38% and 85.79%, respectively. The increase rate of turbulent kinetic energy of SMBR-C is higher than that of SMBR-B (4.41%). The higher turbulence kinetic energy is, the higher turbulence intensity along the membrane channel is. The distributions of turbulent intensity along the membrane channel are shown in Fig. 6. In contrast to SMBR-B, SMBR-C can produce higher turbulent intensity (above 16%), which implies its turbulent degree being stronger. This means that the concentration boundary layer is disrupted and the particle deposition upon the membrane surface decrease due to the introduction of micro-pores. Therefore, the permeate flux of membrane is significantly improved by the MCTP with micro-pores, and membrane fouling can be effectively controlled.
4.1.4. Wall shear stress

The wall shear stress distribution on the flat-sheet membrane surface is depicted in Fig. 9. For SMBR-C, the peak and trough values of wall shear stress are about 4.07 Pa and 1.60 Pa, respectively, and the average value is more than 3.04 Pa. For the SMBR-B, the largest value of wall shear stress is below 2.91 Pa, and the average value is about 2.20 Pa. As to the SMBR-A, the average value is about 1.5 Pa. Comparing with SMBR-A, the increase rate of wall shear stress of SMBR-B and SMBR-C is 46.67% and 102.67%, respectively. The increase rate of wall shear stress of SMBR-C is higher than that of SMBR-B (56.00%). The lower wall shear stress is, the easier cake buildup is. So in order to mitigate membrane fouling, wall shear stress must increase. It has been proved that the high wall shear stress on the membrane surface can effectively reduce the particle deposition on the membrane surfaces, thereby improving the filtration flux [19,20].

From the above analysis, the hydrodynamic performance of SMBR-C is better than that of SMBR-B. Especially, when micro-pores are added in the micro-channel turbulence promoters, it can increase velocity, turbulent kinetic energy, turbulent intensity, wall shear stress and decrease turbulent dissipation rate and pressure drop. Moreover, micro-pores can increase the effective area of membrane. Thus, MCTP with micro-pores can obviously reduce the cake layer thickness and enhance the membrane flux.

4.2. Experimental results

4.2.1. The variation of critical flux and flux

In the process of treating wastewater in SMBR, the filter cake layer is gradually formed when the flux is above the critical flux [28]. It can be seen from Fig. 10 that the critical flux of SMBR-B and SMBR-C is improved. The critical flux of SMBR-A, SMBR-B and
SMBR-C is 42 L/m² h, 53 L/m² h and 68 L/m² h, respectively. The critical flux of SMBR-C is obviously higher than that of the others. Thus, micro-pores added to the micro-channel turbulence promoter can increase the effective membrane area and improve the critical flux of SMBR.

Fig. 11 shows that with time increasing, the flux decreases due to the cake buildup. However, the flux of SMBR equipped with MCTP slowly reduces, especially for the SMBR-C. The flux of SMBR-A suffers almost 80% decline, SMBR-B and SMBR-C are 47.8% and 37.6% in the continuous operation. The reasons for slower flux decline could be explained as follows: firstly, the use of an array of the corrugated MCTP in the SMBR can cause the frequent changes of flow directions and intense velocity fluctuation, which leads to increasing wall shear stress and reducing the cake buildup on the membrane surface. For the corrugated protrusions, the suspension particles are easily adsorbed on the corrugated MCTP-MPs surface which increases suspension particle concentration in the vicinity of the MCTP-MPs and forms small eddies. Secondly, when wastewater flows through the micro-channel, its velocity increases, thereby generating a velocity gradient which can cause the relative movement of particles in suspension, and result in particle collisions, so that the linear macromolecular compounds bridging between deposited biopolymers and inorganic compounds causes homodromous particle flocculation, which increases the particle size and enhances accumulation and pushing, many particles are unable to enter the membrane pore or become stuck in the pole, thus reducing membrane pore clogging. Lastly, micro-pores can increase the effective membrane area and form an anaerobic environment to remove pollutants in order to reduce membrane fouling and improve membrane flux.

4.2.2. The variation of trans-membrane pressure

The rate of trans-membrane pressure (TMP) buildup is an important factor in evaluating membrane filterability in SMBR systems because it is directly related to the extent of membrane fouling [29]. In Fig. 12, the TMPs always increase. At the begin of the experiments, the TMP of SMBR-A slowly increase, the TMP of SMBR-B and SMBR-C is vice versa. But with flux increasing, the TMP rapidly increase for SMBR-A and SMBR-B, and it can be inferred from the above results that the cake on membrane surface is serious at the same time. However, the TMP of SMBR-C slowly increase. This indicated that MCTP with micro-pores could enlarge the TMP operation scope. From Fig. 13, it can be obtained the same results. The main reason is that the corrugated MCTP with micro-pores can stir the fluid to enhance suspension mixing around the membrane surface and decreases particle deposition on the membrane surface, which reduces the cake layer thickness and lessens membrane fouling. And micro-pores can make the suspension particles deposit on the membrane surface to form better compressive and higher porous cake layers, which are easily removed by suspension scouring on the membrane surface.
Table 2
Analysis results of membrane fouling resistance.

<table>
<thead>
<tr>
<th></th>
<th>10^12 m^-1</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SMBR-A</td>
<td>0.0456</td>
<td>2.411</td>
<td>0.658</td>
<td>0.0219</td>
<td>0.704</td>
</tr>
<tr>
<td>SMBR-B</td>
<td>0.0456</td>
<td>0.976</td>
<td>0.548</td>
<td>0.0451</td>
<td>0.593</td>
</tr>
<tr>
<td>SMBR-C</td>
<td>0.0456</td>
<td>0.391</td>
<td>0.298</td>
<td>0.0154</td>
<td>0.343</td>
</tr>
</tbody>
</table>

is 74.98% and FI (B-A) is only 53.34%. With the time increasing, FI (C-A) increases much more than FI (B-A). This suggests that the enhancement effect of SMBR-C on flux is better than that of SMBR-B.

4.2.4. Energy consumption of MBR

From the above analysis, micro-channel turbulence promoter placed in the flat-sheet membrane channel can improve membrane flux while trans-membrane pressure drop is raised. The increase of pressure drop along the membrane channel can lead to a large energy consumption. Thus, the flux improved by the turbulence promoter should be checked with consideration of energy consumption. Figs. 15 and 16 illustrate the variations of hydraulic dissipation power and specific energy consumption. It can be shown from Figs. 15 and 16 that SMBR-C can consume less energy than SMBR-B. SMBR-B and SMBR-C can save energy 5.91% and 34.67%, respectively. That is to say, micro-pores added to micro-channel turbulence promoter can save energy 28.76%.

4.2.5. The analysis of membrane resistance

At the beginning of filtering, the initial flux mainly depends on the self resistance of the new membrane, because the concentration polarization and cake layer resistance are zero. It can be observed from Fig. 17 that the value and variation trend of the total resistance are almost the same in three types of SMBR before 140 mins. Along with the filtration, increasing the cake layer thickness and the number of blocked membrane pores causes an increase concentration polarization and cake layer resistance. The total resistance of SMBR-A increases rapidly, whereas the total resistance of SMBR-B and SMBR-C increase slowly, especially for the SMBR-C. Comparing with SMBR-A, SMBR-B and SMBR-C can decrease the total resistance 42.52% and 88.93%, respectively. That is to say, micro-pores added to micro-channel turbulence promoter can decrease total resistance 46.41%.

The results of resistance distribution following running of the SMBR for six hours are presented in the Table 2. It can be seen that \( R_p \) has a great influence on \( R_t \). In addition, \( R_p \) of SMBR-B and SMBR-C significantly reduces. Especially, SMBR-C can more effectively control the \( R_t \), \( R_c \) and \( R_{ct} \). The final purpose is to control membrane fouling.

5. Conclusions

The hydrodynamic and filtration performance of the corrugated MCTP with micro-pores and without micro-pore in submerged flat-sheet membrane bioreactor has been carried out by CFD simulations and filtration performance experiments. The CFD simulation results and the experimental results showed that the submerged flat-sheet membrane channel equipped with MCTP with micro-pores can increase velocity 10.41%, turbulence kinetic energy 4.41% and wall shear stress 56.00% on the flat-sheet membrane surface, thereby enhancing membrane flux 21.64%, decrease total resistance 46.41% and save energy 28.76% compared with MCTP without micro-pore. Good agreement was found between the CFD simulation results and the filtration experimental results. The reasons could be interpreted as follows: firstly, the use

4.2.3. The variation of flux improvement

Flux improvement (FI) is a very important parameter for evaluating the quality of enhancement mass transfer. In Fig. 14, FI (C-A) is the improvement of permeate flux of SMBR-C; FI (B-A) is the improvement of permeate flux of SMBR-B. It is clear that FI (C-A) is higher than FI (B-A). In six hours, the average value of FI (C-A)

![Fig. 15. Variations of PR with time.](image)

![Fig. 16. Variation of ER with time.](image)

![Fig. 17. Changes of membrane fouling resistance with time.](image)
of an array of the corrugated MCTP with micro-pores in SMBR can cause frequent changes in the flow directions and intense velocity fluctuation, which leads to increasing wall shear stress and reducing cake build-up on the membrane surface. For the corrugated protrusions, the suspension particles are easily adsorbed on the corrugated MCTP-MPs surface which increases suspension particle concentration in the vicinity of the MCTP-MPs and forms smalleddies. Secondly, when wastewater flows through the micro-channels, its velocity increases, thereby generating a velocity gradient which can cause the relative movement of particles in suspension, and result in particle collisions, which enhances accumulation and pushing, many particles are unable to enter the membrane pore or become stuck in the pole, thus reducing membrane pore clogging. Lastly, micro-pores can make the suspension particles deposit on the membrane surface to form better compressive and higher porous cake layers, which are easily removed by suspension scouring on the membrane surface, and increase the effective membrane area and form an anaerobic environment to get rid of pollutants in order to reduce membrane fouling and enhance membrane flux. Furthermore, the development of strategies for MCTP with micro-pores used to control membrane fouling and enhance flux in SMBR can be further researched.

References

学霸图书馆

www.xuebalib.com

本文献由“学霸图书馆-文献云下载”收集自网络，仅供学习交流使用。

学霸图书馆（www.xuebalib.com）是一个“整合众多图书馆数据库资源，提供一站式文献检索和下载服务”的24小时在线不限IP图书馆。

图书馆致力于便利、促进学习与科研，提供最强文献下载服务。

图书馆导航：
图书馆首页 文献云下载 图书馆入口 外文数据库大全 疑难文献辅助工具