Study on the parameters of cleaning water jet for nursing bed hips

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Abstract. In order to study the influence of water jet related parameters in the nursing bed cleaning system on the hip cleaning and comfort of bedridden personnel, combined with the knowledge of ergonomic pressure perception, FLUNET software is used to simulate flow field and analyse impact of nozzle distance to buttock, nozzle diameter, stand-off distance, and jet inclination angle on comfort and cleaning effectiveness of jet stream. When the jet inlet velocity is 3m/s, the stand-off distance is 150mm, the nozzle diameter is 4mm, and the jet tilt angle is 20°, the stand-off distance is 0.0904N, it is within the comfortable pressure range, ranging from 0.0851N~0.0906N. In addition, the jet stream under above settings has a wider cleaning range and meets the cleaning requirement for people lying on nursing bed.

1. Introduction

With the increasing aging of society, the number of people unable to take care of themselves has increased year by year. The society's demand for nursing beds with multiple functions has increased significantly [1], and the demand for nursing beds with sewage collection functions is significantly higher than other functions. However, most nursing beds with the function of collecting waste can only collect excreta, without the ability to clean. Since water jet is effective in cleaning and convenient to use, it is gradually applied to the cleaning of human buttocks. At present, many researchers have conducted a lot of research on applying high-pressure water jets to remove rust, container and pipeline cleaning. Anirban Guha [2] et al. studied the water jet cleaning treatment through experiments and numerical simulations, and concluded that the best cleaning distance and cleanliness value in ultra-high-speed water jet (about 80-200m/s) cleaning; Teimourian H [3] et al. studied the high-speed water jet paint removal and explored the influence of jet parameters on the paint removal effect they concluded that the removal of paint is mainly affected by the combined effect of loading strength and frequency; Zhang [4] et al. analyzed the flow field of the cleaning nozzle of the main drainage pipeline of mine by numerical simulation, and found a linear relationship between shooting force and jet pressure on targeting surface by varying various parameters. Although researchers have conducted extensive research on high-pressure water jet cleaning technology, few researchers have studied the use of low-pressure water jets in the nursing bed sewage collection system to clean the buttocks of long-term bedridden personnel. In this paper, we will study the situation of the water jet used to clean the buttocks of long-term bed-ridden personnel. Combined with the ergonomic pressure sensing related values, the CFD numerical simulation...
method is used to study the effect of the jet flow field on the comprehensive effect of hip cleaning under different influencing parameters.

2. Physical Model and Theoretical Analysis

2.1. Physical Model

When cleaning the buttocks, the buttocks of the bedridden user are located on the air cushion bed. The cylindrical cavity is formed by the wall of the bedpan and the air cushion and the hole between the nozzle and the buttocks. The hip cleaning surface covers the upper part of the cylindrical cavity. Refer to the research of Shi [5] and Wang [6], the standard deviation value was used to establish the hip model. The model of hip cleaning is shown in Figure 1. The model is simplified on the premise that it does not affect the main structural parameters and calculation accuracy. The simplified model is shown in Figure 2.

![Figure 1. Flow field model diagram](image1)

![Figure 2. Simplified model diagram](image2)

2.2. Theoretical Analysis

Due to the fast flow rate of the water in the tube, the Reynolds number is larger and greater than the critical Reynolds number. Therefore the flow state of the jet water in the tube is a turbulent flow. From the Bernoulli equation, the volume flow of the jet water is

\[ q_s = \pi D^2 C_d \sqrt{\frac{2P_s}{\rho}} \]  

(1)

In the formula, \( D \) is the nozzle diameter, \( C_d \) is the flow rate coefficient, \( P_s \) is the jet pressure at the inlet, \( \rho \) is the density of water.

When the jet distance is \( h \), the cleaning area \( S \) of the buttocks surface of the water jet is [7]

\[ S = \pi \left( r + h \tan \frac{\alpha}{2} \right)^2 \]  

(2)

In the formula, \( \alpha \) is the jet inclination angle, \( r \) is the nozzle radius.

According to Newton's second law, the formula for the force of the jet acting on the hip surface is
In the formula, $v_1$ is the velocity at the entrance of the jet, and $v_2$ is the velocity when the jet reaches the target surface.

From formulas (2) and (3), it can be seen that the cleaning area and impact force of the water jet are related to the inclination angle of the jet $\alpha$, the spray distance $h$, the nozzle radius $r$ and the jet stream velocity $v$. In the nursing bed cleaning system, the water channel is pressurized by a pump with a certain power, which leads to a constant jet velocity. In this article, we will study and analyze the effect of hip cleaning by different nozzle radius $r$, spray distance $h$ and jet inclination angle $\alpha$ to determine the parameters of the hip cleaning suitable for long-term bed-riding staff on the nursing bed.

3. Flow Field Analysis

3.1. Theoretical Model

In order to improve the quality of meshing, the tetrahedral core unit is used to mesh the flow field model. Advanced size function is used to perform mesh encryption on the adjacent and curved parts of the key parts of the flow field. The flow field inlet adopts velocity inlet; buttock surface and lower plane are set as pressure outlet, and gauge pressure is 0Pa; the remaining surfaces are set as non-slip wall; the solution model is RNG k-$\varepsilon$ model, because air is used as the medium; the system is a two stream models, Volume of Fluid model is activated RNG k-$\varepsilon$ model is selected. As an improvement to the standard k-model, the $k$ equation and equation [7] in the RNG k-model are as follows:

Equation $k$:

$$
\frac{\partial (p k)}{\partial t} + \frac{\partial (p k u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \alpha_k \mu_{eff} \frac{\partial k}{\partial x_i} \right) + G_k + \rho \varepsilon
$$  \hspace{1cm} (4)

Equation $\varepsilon$:

$$
\frac{\partial (p \varepsilon)}{\partial t} + \frac{\partial (p \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \alpha_k \mu_{eff} \frac{\partial \varepsilon}{\partial x_i} \right) + \frac{C_{\alpha}^{\prime \prime}}{k} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}
$$  \hspace{1cm} (5)

In formulas (4) and (5):

$$
\begin{align*}
\mu_{eff} &= \mu + 0.0845 \rho \frac{k^2}{\varepsilon} \\
C_{\alpha}^{\prime \prime} &= C_{\alpha} - \frac{\eta (1 - \eta / \eta_0)}{1 + \beta \eta} \\
\eta &= (2E_y E_0)^{\frac{1}{2}} \frac{k}{\varepsilon} \\
C_{1e} &= 1.42, C_{2e} = 1.68, \eta_0 = 4.377, \beta = 0.012
\end{align*}
$$  \hspace{1cm} (6)

3.2. Effects of Nozzle Diameter and Spray Distance on Cleaning Speed and Impact Pressure

In order to ensure that the system reduces water without compromising cleaning effect and comfort, the nozzle diameter is set to 2mm, 3mm, 4mm, 5mm and the spray distance $h$ is set to 150mm, 160mm and 170mm. Assuming the distance between the buttocks and the entrance $h = 170$mm and the jet tilt angle
α = 0°, the flow field of the buttock cleaning jet velocity can be obtained as shown in Figure 3. When the diameter of the nozzle is 2mm, after the jet leaves the nozzle, there is a violent momentum and energy exchange with the surrounding air, resulting in a serious atomization of the jet beam, causing a cyclone phenomenon in the flow field, a negative pressure zone [7] is generated near the hip surface due to the influence of the jet stream. The core area of the jet is short, which leads huge momentum loss, and the velocity of jet is \( v_2 = 2.1723 \text{m/s} \) when it contacted the hip surface. When the nozzle diameter is 3mm, the length of the core area of the jet is increased, and the momentum and energy exchange with the surrounding air is improved, but cyclones are generated on both sides of the jet beam, and the velocity of jet stream is \( v_2 = 2.3023 \text{m/s} \) when the jet reaches the buttocks surface. When the nozzle diameter is 4mm and 5mm, the momentum and energy exchange between the jet and the surrounding air is less, the jet stability is better, and the velocity of the jet reaching the buttocks is 2.3811m/s and 2.3937m/s respectively. It can be seen from Figure 3 that the jet flow field can be roughly divided into the initial jet segment and the basic jet segment. The cleaning of the buttock surface mainly occurs in the basic jet segment, which is in line with many proposed method that uses basic jets of water jet to achieve cleaning by R.R. Fernandes [8] and Liu [9].

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\[ \text{Figure 3. Velocity clouds at different nozzle diameters} \]

It can be seen from Table 1 that the gauge pressure value of the flow field with a spray distance of 150mm to 170mm under different nozzle diameters is close to the atmospheric pressure value. As the nozzle diameter increases, the targeting force of the jet on the hip increases. When the spray distance when the diameter exceeds 150mm, the pressure value increases first and then decreases with the increase of the nozzle diameter. The stability of the flow field is relatively poor, and the phenomenon of cyclone occurs. Therefore the stand-off distance is selected to be 150mm.
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**Table 1.** Pressure and targeting force of buttocks facial axis under different nozzle diameters and spray distances

| Serial number | Nozzle diameter /mm | Spray distance /mm | Hip axis pressure /Pa | Central targeting /N |
|---------------|---------------------|-------------------|----------------------|---------------------|
| 1             | 2                   | 150               | -0.0028              | 0.0203              |
|               | 3                   |                   | 0.0434               | 0.0500              |
|               | 4                   |                   | 0.0579               | 0.0920              |
|               | 5                   |                   | 0.1043               | 0.1455              |
| 2             | 2                   | 160               | -0.0120              | 0.0202              |
|               | 3                   |                   | 0.0219               | 0.0495              |
|               | 4                   |                   | 0.0641               | 0.0908              |
|               | 5                   |                   | 0.0621               | 0.1436              |
| 3             | 2                   | 170               | -0.0072              | 0.0200              |
|               | 3                   |                   | 0.0106               | 0.0490              |
|               | 4                   |                   | 0.0209               | 0.0896              |
|               | 5                   |                   | 0.0176               | 0.1416              |

The relationship between jet center velocity and stand-off distance at four nozzle diameters at the jet axis is generated in Matlab software as shown in Figure 4. It can be found from the analysis that as the jet distance increases, the velocity of the jet center decreases and the velocity decay rate will decrease with the diameter of the nozzle. The axial pressure on the hip surface will increase first and then decrease, when the nozzle diameter is 4mm, the axial pressure is 0.0209Pa. When the jet distance is 0~80mm, the jets of the four nozzle diameters all have a large velocity attenuation rate and exhibit oscillating attenuation; after the jet distance exceeds 80mm, the jet velocity continues to show oscillating attenuation with the increase of the injection distance under the conditions of nozzle diameters of 2mm and 3mm, but the attenuation rate decreases. The jet velocity is negatively linearly related to the jet distance when the nozzle diameter is 4mm and 5mm. As the diameter of the jet nozzle increases, the velocity of the jet reaching the buttock face increases, but when the nozzle diameter exceeds 4mm, the speed difference at the hip surface decreases.

![Figure 4. Curves of speed variation with jet distance under different nozzle diameters](image-url)
The relationship between the lateral distance of the buttocks and the jet velocity is shown in Figure 5. From the figure, the relationship between the jet velocity at the buttocks and the lateral distance is approximately normally distributed. As the distance from the jet cleaning center increases, the velocity of the buttocks jet gradually decreases. Considering the centralized cleaning of the buttocks by the jet, the flushing area should not be too large, so the circle with a radius $r = 30\text{mm}$ is selected as the buttock cleaning surface. The jet velocity when the lateral distance of the buttocks surface from the center is 30mm is shown in Table 2. It can be drawn from Table 2 that as the diameter of the entrance increases, the speed of reaching the hip surface increases and the rate of increase gradually decreases. It can be seen that when the inlet diameter is 2mm and 3mm, the jet flow loss is large, the jet center velocity and the central targeting force value are small, and it cannot meet the needs of hip cleaning.

![Figure 5. Curve of relationship between lateral distance of buttocks and jet velocity](image)

**Table 2.** Hip surface speed when the horizontal distance from the central axis is 30mm

| Serial number | Inlet diameter /mm | Hip speed /m·s$^{-1}$ |
|---------------|--------------------|-----------------------|
| 1             | 2                  | 0.4622                |
| 2             | 3                  | 0.7558                |
| 3             | 4                  | 1.1108                |
| 4             | 5                  | 1.2750                |

### 3.3. Influence of Jet Tilt Angle on Hip Cleaning

From the literature [5], it can be seen that the average value of the hip convexity of young women is 112.5mm, the injection angle is 18.43° when the jet distance $h=150\text{mm}$, the half of the hip protrusion is 50mm, and the jet tilt angle $\alpha$ is defined as the inlet central axis and the jet central axis. Taking spray angles of 10°, 15°, and 20°, and spray distance of 170mm, and nozzle diameters of 4mm and 5mm and center velocity of the jet and targeting force at central axis are simulated. Simulation results are shown in Table 3.
### Table 3. Jet velocity and targeting force at the buttocks under different schemes

| Entrance hole diameter /mm | Scheme | Jet tilt angle /° | Standoff distance /mm | Jet center velocity /m·s⁻¹ | Central targeting /N |
|---------------------------|--------|------------------|----------------------|----------------------------|---------------------|
| 4mm                       | 1      | 10               |                      | 2.4522                     | 0.0923              |
|                           | 2      | 15               |                      | 2.4296                     | 0.0915              |
|                           | 3      | 20               | 150                  | 2.4003                     | 0.0904              |
| 5mm                       | 4      | 10               |                      | 2.4641                     | 0.1451              |
|                           | 5      | 15               |                      | 2.4630                     | 0.1450              |
|                           | 6      | 20               |                      | 2.4486                     | 0.1441              |

It can be seen from Table 3 that at the same injection distance, with the increase of the jet tilt angle, the jet center velocity and the center targeting force will decrease; when the jet inclination angle is 10°, the jet velocity at the two incident apertures is the largest, the speed is 2.3768m/s, 2.4037m/s; under the same jet inclination angle, as the nozzle diameter increases, the jet center velocity increases. Since the cleaning of the buttocks mainly depends on the impact damage of the kinetic energy of the jet on the dirt surface of the buttocks, the inclination angle of the jet with a larger jet velocity and the central targeting force value should be selected. At the same time, considering that the jet is used to clean the buttocks of long-term bed-ridden personnel, the skin of the hips of such personnel is relatively fragile, and it will cause discomfort such as pain when subjected to a large impact force. With reference to Tan [10] et al.’s research on the corresponding changes of the human body under the impact of the impact force, combined with the size of the hip cleaning area, it is determined that the nozzle diameter is 4mm and the jet inclination angle is 20°.

### 4. Conclusion

1. From analysis of simulation of the flow field of the water jet cleaning hips of the bedridden, We conclude that jet flow field contains the initial segment and the basic segment, and the basic segment is used to clean the hips of the bedridden, which are consistent with existing results.

2. When the jet distance and the jet tilt angle are constant, through the simulation and comparison of the jet flow velocity at different nozzle diameters, we found that the jet nozzle diameter under low jet velocity is positively correlated with central targeting force. When the nozzle diameter exceeds a certain value, the difference in jet flow velocity decreases and the rate of change in velocity will converge.

3. When the nozzle jet velocity is constant, the smaller the nozzle, the greater the loss of momentum of jet flow. When the nozzle diameter is less than 4mm, the stability of the flow field is poor. As the distance of the jet increases, the flow field vortexes a large energy exchange occurs between the jet stream and the surrounding medium and the jet velocity demonstrated an oscillating decay pattern.

4. When the stand-off distance is fixed, the jet velocity and center targeting force are negatively correlated with the jet tilt angle. Combined with the knowledge of ergonomic pressure perception, it was finally determined that the inclination angle of the jet was 20°, the diameter of the entrance hole was 4mm, and the stand-off distance was 150mm.

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