IJIE

INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 18 No. 2 (2026) 126-140
https://publisher.uthm.edu.my/ojs/index.php/ijie

Effect of Groove Height on Hydraulic Performance of Spiral Corrugated Firefighting Pipe

Gercham Gan[1], Normayati Nordin[1]*, Mohd Sukri Ramli[2], Azian Hariri[1], Akmal Nizam Mohammed[1]

[1] *Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA*

[2] *Taehwa Engineering Sdn. Bhd, No.99, Jalan TJ 3/2D, Senawang Link, Kawasan Industri Tuanku Jaafar, 71450, Sungai Gadut, Negeri Sembilan, MALAYSIA*

*Corresponding Author: mayati@uthm.edu.my
DOI: https://doi.org/10.30880/ijie.2026.18.02.011

Article Info

Received: 25 August 2025
Accepted: 30 December 2025
Available online: 28 April 2026

Keywords

Spiral corrugated pipe, firefighting, hydraulic performance, friction factor, flow uniformity

Abstract

Corrugated pipes are recognized for their strength, flexibility, and ease of installation, making them suitable for various industries, including firefighting systems. Unlike conventional firefighting systems that typically use rigid and fixed-length pipes, corrugated pipes can be easily retrofitted, particularly in confined or irregular spaces. However, due to their complex geometry, predicting the performance of corrugated pipes remains a challenge. This study numerically investigates the hydraulic performance of spiral corrugated pipes applied in firefighting systems. It specifically examines the effect of groove height on the friction factor and flow uniformity to determine optimal design configurations. Computational Fluid Dynamics (CFD) was employed, and the RNG k-ε turbulence model was validated as the most effective, demonstrating a numerical deviation ±5%. The results demonstrate that the friction factor is notably affected by the corrugation due to the presence of secondary backflow vortices within cavities, resulting in intensified turbulence, increased flow resistance, and greater wall friction. Minimal performance disruption, however, is demonstrated for the flow uniformity as strong vortices and mixing turbulence enhance the flow homogeneity. The groove height, k/D_{int}= 0.015 is regarded as the most optimal, yielding a balanced hydraulic performance with an effective friction factor while maintaining flow uniformity. Overall, spiral corrugated firefighting pipes may be required due to design or structural constraints, but they could have hydraulic performance deficiencies of up to 60% compared to conventional smooth pipes.

1. Introduction

Fire sprinkler systems are one of the most reliable fire protection measures applied in modern building design. The system is designed to automatically release water when a fire is detected, where the system is suppressing or controlling the fire from spreading [1]. For decades, fire sprinkler systems have depended on materials such as galvanized steel, black iron and CPVC, which are rigid pipes to deliver pressurized water to the sprinkler head. This conventional system has proven reliable, however, there is still a drawback. It would take a toll on the installation process, especially in confined or irregularly shaped spaces. Due to their inflexibility, the system often forces the engineer and contractor to work around the structural limitation, which will consume time and cost for the whole project [2]. The reliability of a fire sprinkler system depends not only on the performance of the sprinkler heads but also fundamentally on the integrity and efficiency of the piping layout. A well-designed piping system must ensure sufficient flow rates and maintain pressure levels across a distributed network, particularly during emergency scenarios [3].

To address these limitations, researchers and engineers have turned to innovative alternatives, including flexible corrugated pipes, which have been used in countries like China and Korea [4, 5]. Table 1 summarises previous works related to the parametric study of corrugated pipe. Unlike rigid piping, corrugated pipes feature a flexible design that combines strength with flexibility, simplifying installation and improving adaptability across diverse applications [6]. Square grooves are categorized into two types, k-type and d-type, based on their length-to-height ratio. Perry et al. [7] demonstrated that increasing the groove height ratio (ω/k), where ω is groove length and k is groove height, led to a reduction in friction factors, a trend linked to intensified vortex formation and stronger flow disturbances within the grooves. This phenomenon aligns with the observations in k-type grooves, where the primary flow penetrated the groove due to its length exceeding its height and generated vortices localized near the corners, further influencing the overall flow dynamics [8]. In d-type, where height exceeds length, the vortex filled the cavity, decoupling it from the main flow. Reducing the pitch-to-height ratio (p/k) in d-type corrugated pipes significantly lowered pressure drops, particularly in high Reynolds number conditions [5].

Advancements in computational power have made Computational Fluid Dynamics (CFD) a reliable tool for analysing complex fluid flows and complementing experimental work [9, 10, 11]. The CFD simulation showed the increment on both corrugation height and frequency boosts flow turbulence and friction factor, significantly improving heat transfer at the cost of greater flow resistance [12]. For d-type corrugated pipes, groove width significantly affected the friction factor more than groove height, demonstrating a log-linear dependence on Reynolds number [13]. The findings indicated that pipe corrugations significantly increased flow resistance and pressure drop, with these effects being particularly pronounced in geometries featuring taller protrusions and closer spacing [14]. The study revealed that corrugated pipe geometries induced significantly higher pressure drops than smooth pipes, primarily due to groove-induced flow disturbances [15]. The study demonstrated that corrugated tubes exhibited an increment of 1.73 to 2.09 in pressure drop compared to smooth tubes, primarily due to enhanced turbulent mixing and wall friction induced by the periodic corrugation geometry [16]. The flow characteristic occurred in the helical corrugations, increasing friction factors by 1.46 to 1.93 compared to smooth tubes, where greater rib-height ratios and tighter pitch spacing generated stronger secondary flows and form drag, simultaneously improving thermal performance at the cost of hydraulic efficiency [17]. Larger groove lengths and higher Reynolds numbers increased the friction factor and near-wall turbulence, as flow interactions within the grooves intensify shear stresses and energy losses [18]. The flow resistance coefficients of the spiral corrugated pipe were 89–324% higher than the smooth pipe [19].

Overall, corrugated pipes have received a considerable amount of research regarding the flow performance that occurs in the transverse corrugated pipe. The general differences that separate the transverse corrugated pipe and spiral corrugated pipe are that the transverse corrugated pipe has grooves arranged perpendicular to the pipe axis, whereas the spiral corrugated pipe features helical grooves that wrap around the pipe along its length. Prior works have systematically investigated geometric parameters of grooves, demonstrating that increased groove height facilitates stronger flow interaction within the groove cavities and between the core flow and recirculation zones. Despite their potential advantage for fire sprinkler systems, research on spiral corrugated pipes remains poorly characterized in terms of fluid dynamics. This knowledge gap becomes particularly crucial as the industry shifts from conventional pipe to flexible corrugated pipe.

Table 1 *Previous works related to flow in corrugated geometries*

Reference	Method	Corrugation	*Re*	*k/D*
Shahneoug et. al [12]	FEM	Sinusoidal	150-314	0-0.07952
Stel et. al [13]	CFD	d-type	5000-10000	0.015-0.045
Córcoles et. al [14]	CFD	Spiral	25000	0.028-0.075
Kashiwakura et. al [15]	Experiment	Transverse	2300	0.03-0.04
Shenglin et. al [16]	CFD	Transverse	-	0.06
Pethkool et. al [17]	Experiment	Helical	5500-60000	0.02-0.06
Henrique et. al [18]	Experiment & CFD	d- type	5000-10000	0.03-0.04
Li et. al [19]	Experiment & CFD	Helical	429-6212	0.104

Int. Journal of Integrated Engineering Vol. 18 No. 2 (2026) p. 126-140

Therefore, this study aims to conduct a parametric study on spiral corrugated pipe to primarily investigate the influence of geometrical parameter - groove height on the hydraulic performances - friction factor and flow uniformity. The optimal configuration of groove height is ultimately proposed.

2. Methodology

The parametric study was numerically conducted using ANSYS CFD code FLUENT. The effect of groove height on the hydraulic performance of spiral corrugated firefighting pipes was investigated.

2.1 Modelling and Meshing

The conventional smooth pipe geometric configuration as a baseline case is presented in Fig. 1, with its dimensional specifications summarized in Table 2. Meanwhile, the geometry of the spiral corrugated pipe is shown in Fig. 2, and its specifications are summarized in Table 3. Both configurations were modeled and simulated based on the actual product used in the existing system.

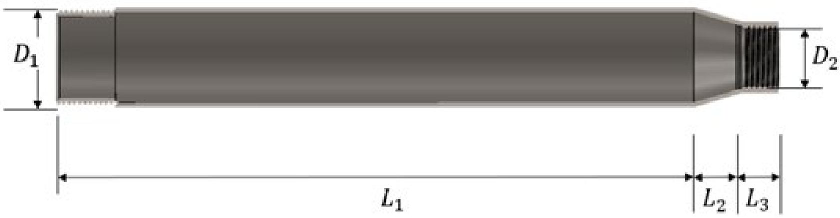


Fig. 1 *Geometrical model of a conventional smooth pipe*

Table 2 *Specifications of a conventional smooth pipe*

Parameter	Dimension
Inlet diameter, D_1	19.0 mm
Outlet diameter, D_2	14mm
Reducer length, L_1	209.5 mm
Nozzle length, L_2	14.0 mm
Orifice length, L_3	11.5 mm
Nozzle angle, α	14°
Discharge coefficient, K gpm/psi$^{1/2}$ (L/min/bar$^{1/2}$)	5.6 (80)

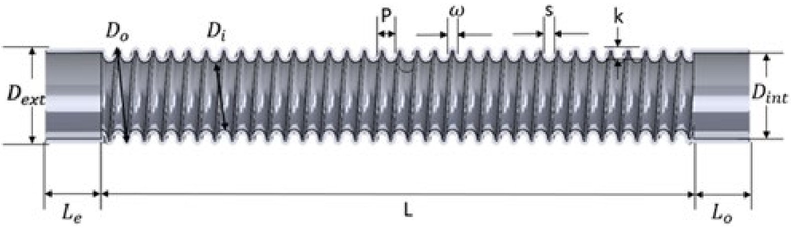
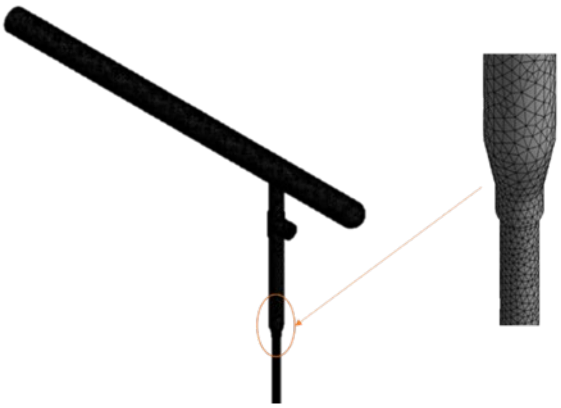


Fig. 2 *Geometrical model of a spiral corrugated pipe*

Table 3 *Specifications of a spiral corrugated pipe*

Parameter	Dimension
External diameter, D_{ext}	25.2 mm
Internal diameter, D_{int}	24.7 mm
Outer diameter of corrugation, D_o	25.8 mm
Inner diameter of corrugation, D_i	22.3 mm
Groove height, k	1.75 mm
Groove pitch, P	5.5 mm
Groove length, ω	4.1 mm
Distance between grooves, s	1.4 mm
Entrance length, L_e	78.0 mm
Corrugation length, L	1452 mm
Outlet length, L_o	72.0 mm
Revolution (revs)	266
Discharge coefficient, K gpm/psi$^{1/2}$ (L/min/bar$^{1/2}$)	5.6 (80)

The computational model was discretized using tetrahedral meshes as shown in Fig. 3. Mesh quality was systematically evaluated, with the average skewness kept below 0.30 and orthogonality maintained close to 1.0 [20]. Local refinement was applied at critical areas, including pipe joints and curvature transitions, where flow separation and secondary motions are anticipated [21]. The final mesh demonstrated consistent quality metrics throughout the domain, with all elements meeting specified thresholds for skewness and orthogonality. This meshing strategy produced a computational grid comprising 156,811 elements and 69,274 nodes, with the skewness and orthogonal value satisfying the recommended quality criteria.


(a)

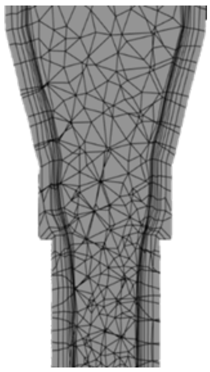

(b)

Fig. 3 *Generated tetrahedral meshes (a) Surface mesh; (b) Cross-section mesh*

2.2 Solver Setting and Boundary Conditions

The numerical analysis was conducted by solving the following governing equations for three-dimensional, steady-state, and incompressible flow:

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (1)$$

x-momentum equation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+v\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right]+\frac{1}{\rho}\left[\frac{\partial\left(-\rho\overline{u'^2}\right)}{\partial x}+\frac{\partial(-\rho\overline{u'v'})}{\partial y}+\frac{\partial(-\rho\overline{u'w'})}{\partial z}\right] \quad (2)$$

y-momentum equation:

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\upsilon\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right]+\frac{1}{\rho}\left[\frac{\partial(-\rho\overline{u'v'})}{\partial x}+\frac{\partial\left(-\rho\overline{v'^2}\right)}{\partial y}+\frac{\partial(-\rho\overline{v'w'})}{\partial z}\right] \quad (3)$$

z-momentum equation:

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial z}+\upsilon\left[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right]+\frac{1}{\rho}\left[\frac{\partial(-\rho\overline{u'w'})}{\partial x}+\frac{\partial(-\rho\overline{v'w'})}{\partial y}+\frac{\partial\left(-\rho\overline{w'^2}\right)}{\partial z}\right] \quad (4)$$

The boundary conditions for both conventional and spiral corrugated pipes, as specified in Table 4, were applied. Three k-ε turbulence models (standard, RNG, realizable) were considered for simulations, with the most optimum validated with the actual experimental work by Gan [22]. The solution framework employed SIMPLEC pressure-velocity coupling, second-order discretization schemes with enhanced wall treatment, $y+ \approx$ 1-5, and all residuals converged below a 10^{-5} threshold.

Table 4 *Boundary conditions for conventional smooth and spiral corrugated pipes*

Boundary Type	Conventional Pipe			Spiral Pipe		
	Velocity (m/s)	Turbulent Intensity (%)	Hydraulic diameter (m)	Velocity (m/s)	Turbulent Intensity (%)	Hydraulic diameter (m)
Inlet	0.1115	5.33	0.053	0.0993	5.41	0.053
	0.1686	5.06	0.053	0.1546	5.11	0.053
	0.2320	4.86	0.053	0.1958	5.00	0.053
	0.2597	4.79	0.053	0.2338	4.86	0.053
	0.3468	4.62	0.053	0.2760	4.76	0.053
	Gauge Pressure (Pa)	Turbulent Intensity (%)	Hydraulic diameter (m)	Gauge Pressure (Pa)	Turbulent Intensity (%)	Hydraulic diameter (m)
Outlet	0	4.55	0.015	0	4.62	0.015
	0	4.32	0.015	0	4.37	0.015
	0	4.15	0.015	0	4.24	0.015
	0	4.09	0.015	0	4.15	0.015
	0	3.95	0.015	0	4.06	0.015

The hydraulic performance of pipes was assessed primarily in terms of friction factor (*f*) and flow uniformity (σ_{out}). Both indices are expressed as follows:

Friction factor:

$$f=\frac{2d\Delta P}{\rho u^2 L} \quad (5)$$

Where:

d= diameter (m)
ΔP= Pressure drop (Pa)
ρ= Density (kg/m3)
u= Velocity (m/s)
L= Length (m)

Flow Uniformity Index:

$$\sigma_{out}=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(V_i-V_{out})^2} \quad (6)$$

Where: *N*= Number of measurement points
V_i= Local outlet air velocity (m/s)
V_{out}= Mean outlet air velocity (m/s)

2.3 Parametric Study for Optimal Configuration

A parametric study was conducted to investigate the effects of groove height (k/D_{int}) on friction factor and flow uniformity within 7 to 12 bar pressure input (corresponds to Re = 2.664 x 10^4 – 3.999 x 10^4). As presented in Table 5, (k/D_{int}) was varied from 0.015 to 0.0795. Fig. 4 shows the corrugated pipe geometry variation considered.

Table 5 *Corrugation groove height ratio (k/Dint) specs*

No	k/D_{int}	k (mm)	D_{int} (mm)
a	0.0150	0.3705	24.7
b	0.0389	0.9608	24.7
c	0.0528	1.3042	24.7
d	0.0710	1.7500	24.7
e	0.0795	1.9637	24.7

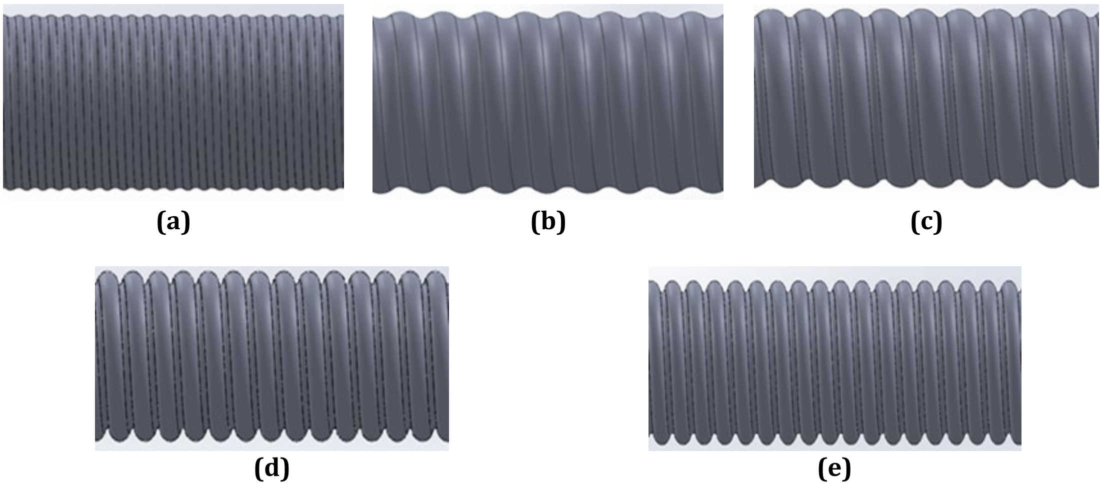


Fig. 4 *Variation of groove height (k/Dint) (a) 0.0150; (b) 0.0389; (c) 0.0528; (d)0.0710; (e) 0.0795*

The optimal configuration was determined by assigning a weightage factor, which was inversely multiplied by the corresponding value of the friction factor (f) and flow uniformity (σ_{out}) as demonstrated in Eq. (7). The assigned weightage factor was determined based on the objective of reflecting its importance in determining the optimum configuration. A weightage factor of 0.6 was prioritized for the friction factor, as reducing flow resistance was the primary objective of this study, followed by flow uniformity with a weightage of 0.4.

The following equation was applied to assign the optimal configuration rank of both groove heights and Reynolds numbers:

$$Total\ Score = \left(\frac{1}{f \times W}\right) + \left(\frac{1}{\sigma_{out} \times W}\right) \quad (7)$$

Where:

f = friction factor
σ_{out}= flow uniformity index
W= weightage factor (0.6 for friction factor and 0.4 for flow uniformity)

2.4 Grid Independence Test (GIT)

A systematic Grid Independence Test (GIT) was conducted on the conventional smooth pipe and the spiral corrugated pipe to determine the optimal configuration, where changes in the element number and number of nodes do not influence the accuracy of the result. The results presented in Fig. 5 demonstrate that the solution begins to stabilize when the mesh density exceeds 400,000 elements, indicating GIT convergence for a system. At this threshold, further refinement of the mesh density shows negligible impact on the solution accuracy. A relative error analysis was conducted to determine the optimal number of elements for subsequent velocity studies. Based on these results, a mesh consisting of 400,000 elements with y+=4 was deemed optimal as the results obtained have the least relative error compared to experimental data, providing a balance between computational efficiency and solution accuracy, and was therefore selected for all subsequent velocity investigations.

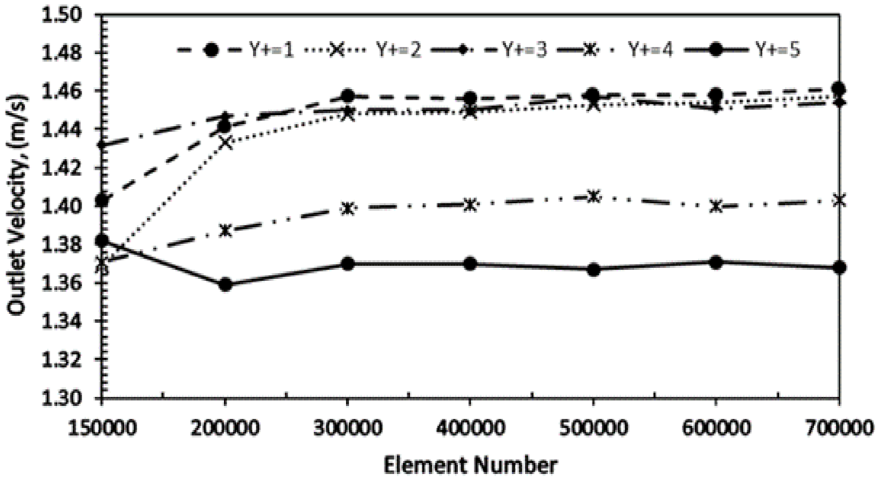


Fig. 5 *Grid Independence Test (GIT) by varying* **y^+**≈*1-5*

3. Result and Discussion

The effects of groove height on hydraulic performance (friction factor and flow uniformity) of spiral corrugated firefighting pipes are analyzed and discussed, with the most optimal configuration ultimately proposed. The analysis is subject to numerical discrepancies not exceeding ±5%.

3.1 Numerical Validation

The applicability and validity of three k-ε turbulence models (Standard, RNG, Realizable) were assessed by comparing the simulation results with the actual experiment for both conventional smooth and spiral corrugated firefighting pipes [22]. The RNG k-ε turbulence model demonstrates the closest agreement to the actual, with a deviation of 4.28% for corrugated pipe, while for conventional pipe, the Standard k-ε turbulence proves to be the most reliable, with a deviation of only 0.64%. Table 6 summarizes the numerical validation results.

Further verification was conducted by applying the validated turbulence models to various inlet velocity conditions, as shown in Fig. 6, which demonstrated strong agreement with the experiment. The minor observed discrepancies are due to idealized wall boundary conditions that neglect measured surface roughness, geometric simplifications in the corrugation profiles, and unaccounted manufacturing tolerances in the physical test specimen. These results confirm the model's validity for engineering analysis while suggesting potential improvements through the implementation of advanced wall functions or local mesh refinement near corrugation peaks.

Table 6 *Numerical validation results*

Firefighting Pipe	CFD Model	Simulated Velocity (m/s)	Actual Velocity [22] (m/s)	Numerical Deviation (%)
Conventional Smooth	Standard	1.401		0.64
	RNG	1.405	1.392	0.93
	Realizable	1.405		0.93
Spiral Corrugated	Standard	1.181		4.68
	RNG	1.186	1.239	4.28
	Realizable	1.183		4.58

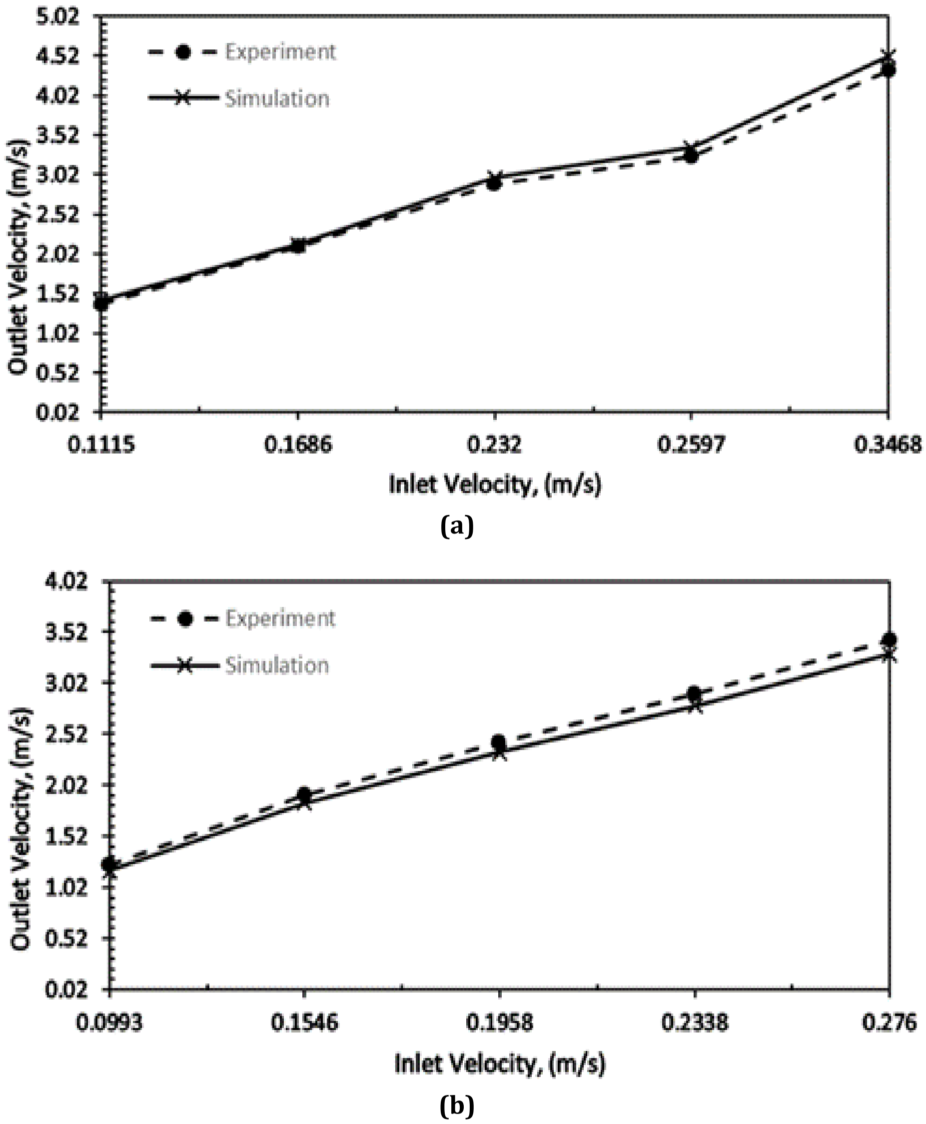


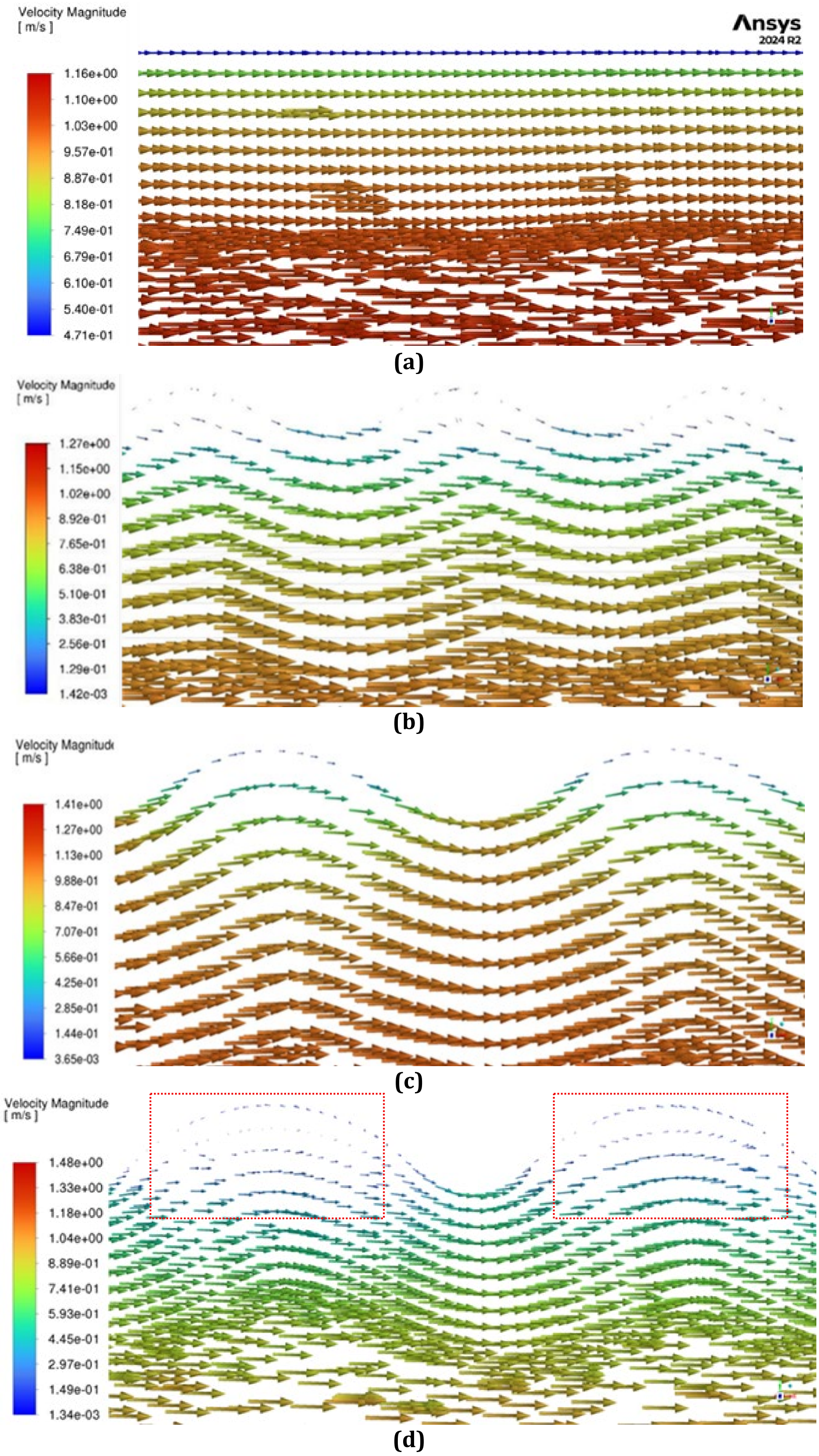
Fig. 6 *Validating Standard and RNG k-ε turbulence model for respectively (a) Conventional; and (b) Corrugated pipes at various inlet velocities*

3.2 Effect of Groove Height on Friction Factor

Fig. 7 shows the flow vector of spiral corrugated pipes in comparison to that of a smooth conventional pipe. The onset of backflow is noted to occur at k/D_{int} = 0.05280, with more pronounced secondary flow vortices observed at taller protrusions, k/D_{int}=0.0710 to 0.0795. Consequently, the friction factor of spiral corrugated pipes is found to be, on average 336% higher than the smooth pipe.

The effect of groove height (k/D_{int}) on the friction factor (f) of spiral corrugated firefighting pipes, in comparison to a baseline case, is depicted in Fig. 8. The results indicate that introducing spiral corrugation (k/D_{int}=0.0150 to 0.07950) increases the friction factor by 0.05 to 0.10 compared to the baseline smooth pipe (k/D_{int}=0). This increase is attributed to the periodic grooves that generate secondary flow vortices, resulting in enhanced turbulent mixing, increased flow resistance, and greater wall friction.

Hong et al. [8]demonstrated that upon establishment of a vortex form within the groove cavity, further increasing the groove height after a certain point has minimal impact on the main flow. Similarly, Pethkool et al. [17] observed this trend in helically corrugated pipes, where an increase in rib heights (k/D_{int}) resulted in higher friction factors; however, the rate of increase became less pronounced at greater depth. In the present work, this same trend is evident, as only nominal changes in the friction factor are observed upon introducing deeper grooves, starting from k/D_{int}= 0.05280.


Velocity Magnitude
[m/s]
Ansys
2024 R2
1.16e+00
1.10e+00
1.03e+00
9.57e-01
8.87e-01
8.18e-01
7.49e-01
6.79e-01
6.10e-01
5.40e-01
4.71e-01
(a)
Velocity Magnitude
[m/s]
1.27e+00
1.15e+00
1.02e+00
8.92e-01
7.65e-01
6.38e-01
5.10e-01
3.83e-01
2.56e-01
1.29e-01
1.42e-03
(b)
Velocity Magnitude
[m/s]
1.41e+00
1.27e+00
1.13e+00
9.88e-01
8.47e-01
7.07e-01
5.66e-01
4.25e-01
2.85e-01
1.44e-01
3.65e-03
(c)
Velocity Magnitude
[m/s]
1.48e+00
1.33e+00
1.18e+00
1.04e+00
8.89e-01
7.41e-01
5.93e-01
4.45e-01
2.97e-01
1.49e-01
1.34e-03
(d)

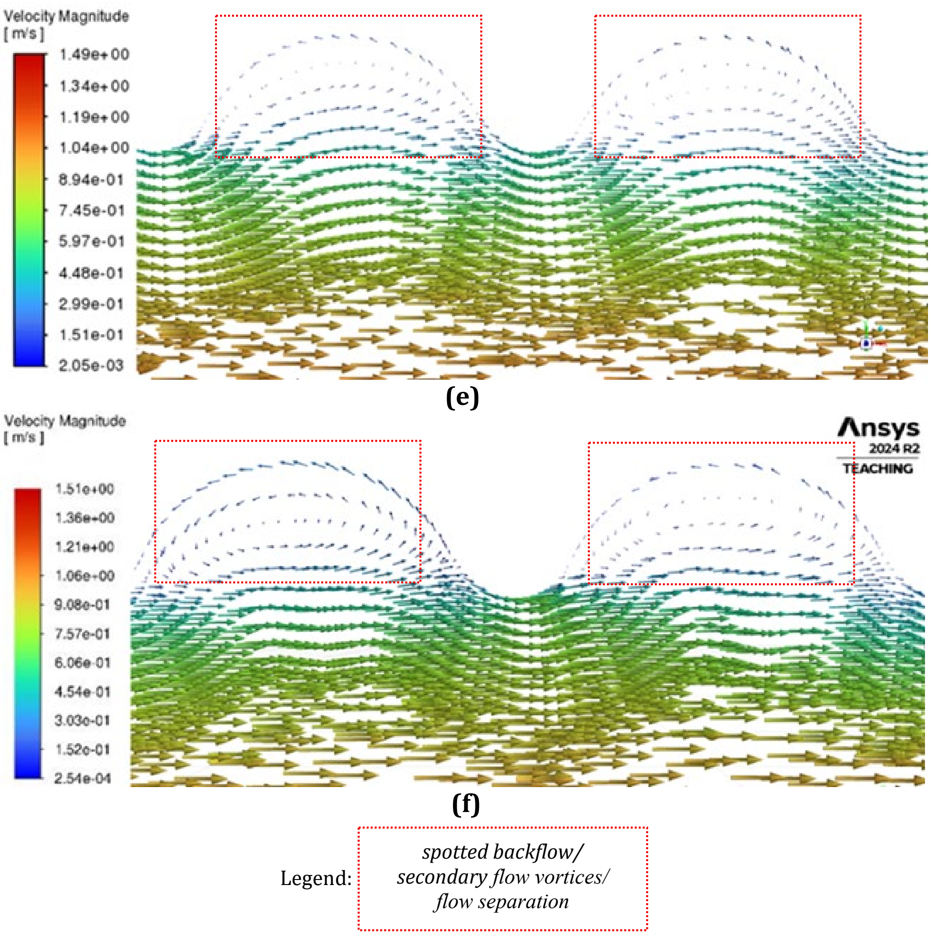


Fig. 7 *Vector flow of the spiral corrugated pipe with different groove heights (a) smooth – baseline k/Dint=0; (b) k/Dint=0.0150; (c) k/Dint=0.0389; (d) k/Dint=0.0528; (e) k/Dint=0.0710; (f) k/Dint=0.0795*

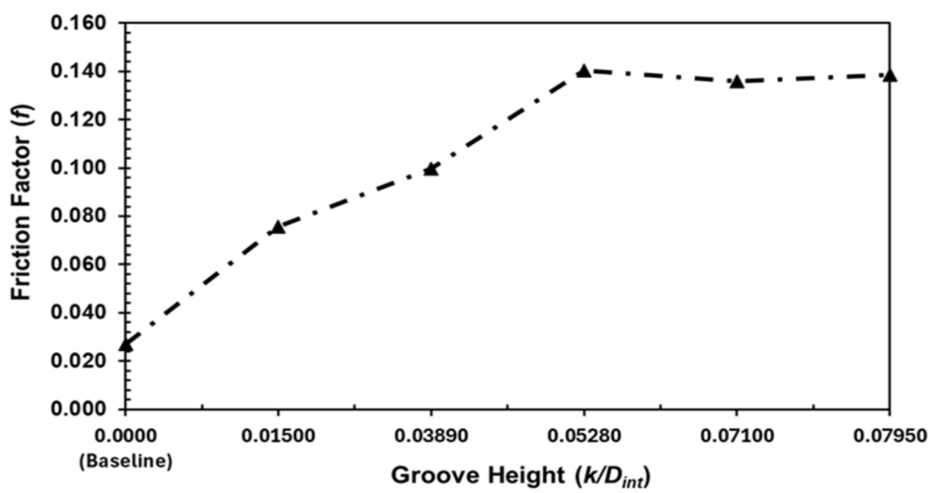


Fig. 8 *Effect of groove heights (k/Dint) on friction factor (f) of spiral corrugated firefighting pipes*

3.3 Effect of Groove Height on Flow Uniformity

The flow performance can be evaluated primarily in terms of flow uniformity, σ_{out}, which represents the mean standard deviation of outlet velocity. The least absolute deviation corresponds to the greatest uniformity of flow [20, 21]. Fig. 9 presents the effect of groove height (k/D_{int}) on the flow uniformity (σ_{out}) of spiral corrugated firefighting pipe, in comparison to a baseline case. The flow uniformity only experiences a slight disruption

Int. Journal of Integrated Engineering Vol. 18 No. 2 (2026) p. 126-140

compared to the baseline, averaging 5.5% as k/D_{int} increases from 0.0150 to 0.0795. These findings demonstrate that adding corrugation does not significantly affect the flow uniformity.

In fact, at a relatively deeper groove, starting from k/D_{int}=0.0389, the flow uniformity nearly reaches the optimal baseline level. This promising performance results from strong vortices and mixing turbulence generated within the groove cavities, which promote more homogeneous flow distribution. Besides, Nordin et al. [21] have proven that the flow uniformity was influenced significantly by the dispersion of the core and secondary flow. The outlet velocity contour shown in Fig. 10 illustrates clearly the homogeneity and uniformity of flow distribution as the k/D_{int} increases.

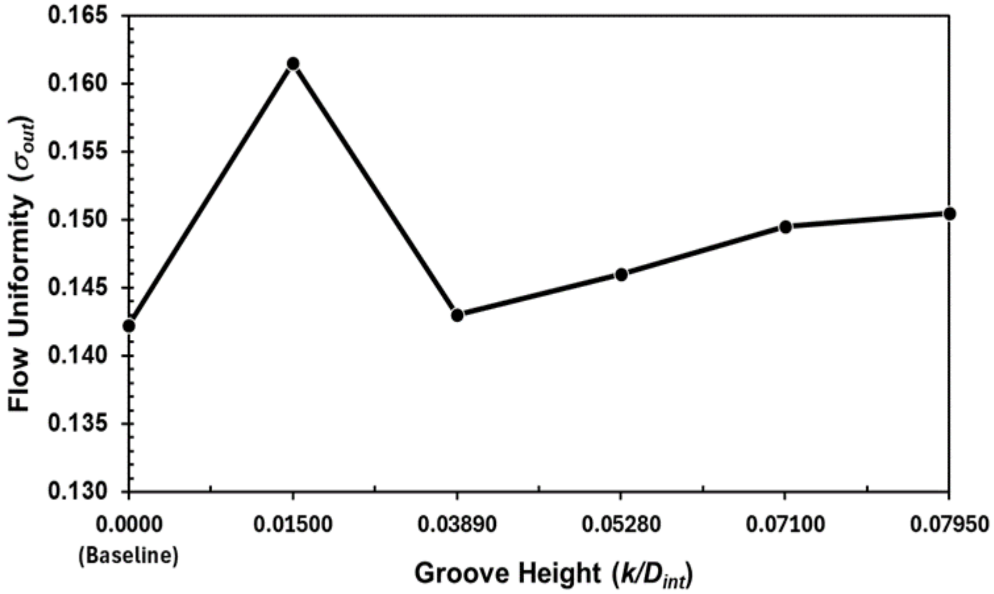


Fig. 9 *Effect of groove heights (k/Dint) on flow uniformity ($\boldsymbol{\sigma_{out}}$) of spiral corrugated firefighting pipes*

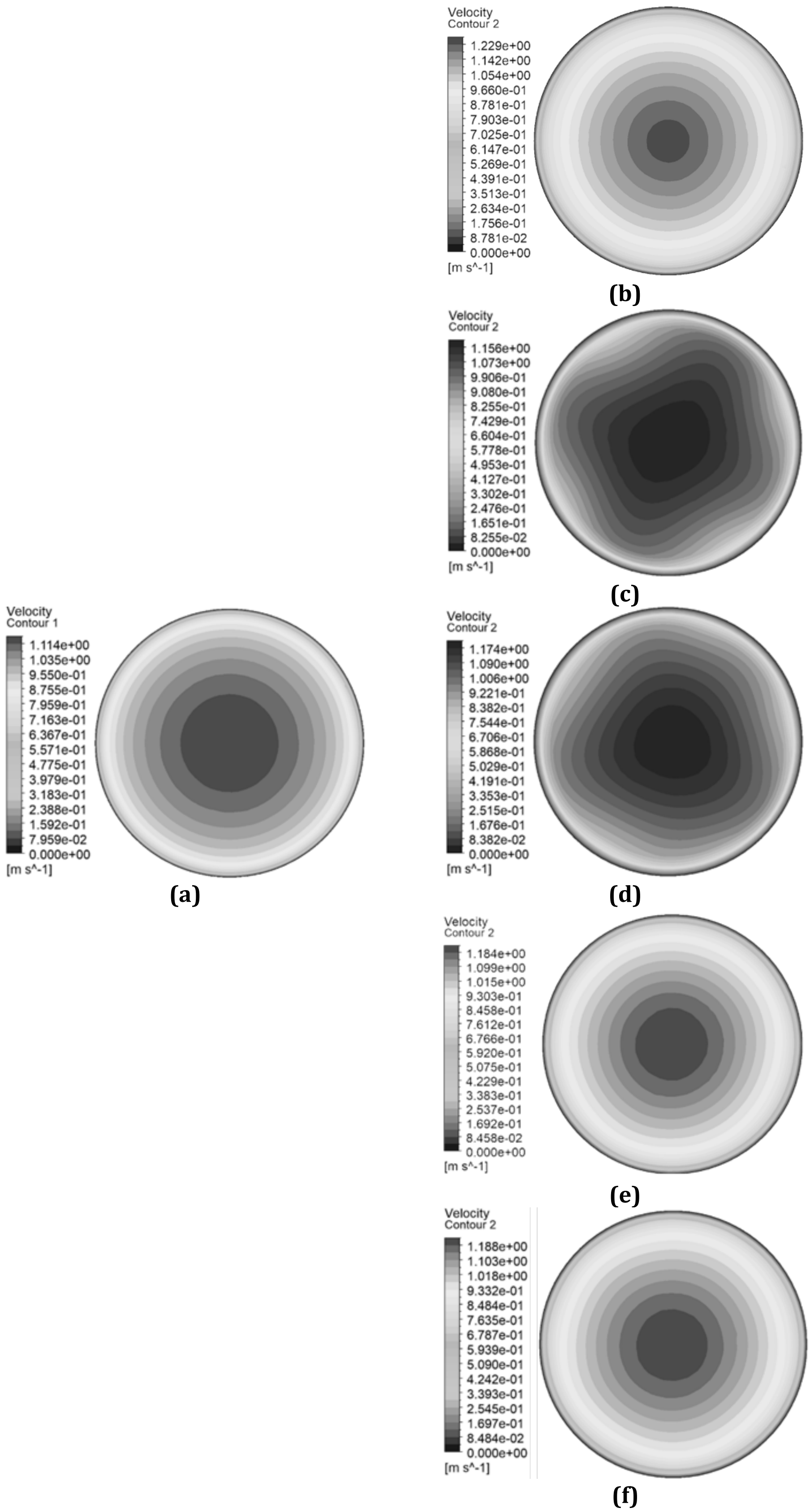


Fig. 10 *Outlet flow distribution contour of spiral corrugated pipes with different groove heights (a) smooth-baseline k/Dint=0; (b) k/Dint=0.0150; (c) k/Dint=0.0389; (d) k/Dint=0.0528; (e) k/Dint=0.0710; (f) k/Dint=0.0795*

3.4 Optimal Groove Heights for Hydraulic Performance of Firefighting Pipe

Fig. 11 presents the effect of groove height on the hydraulic performances of spiral corrugated pipes. The optimal configuration of groove height is determined based on a trade-off between friction factor and flow uniformity. A weightage of 60% is assigned to the friction factor, since minimizing flow resistance is the main objective, while flow uniformity is given a weightage of 40%. Table 7 finalizes the optimal groove height rank for spiral corrugated firefighting pipes.

Groove height (k/D_{int} =0.015) is regarded as the most optimal, yielding a balanced hydraulic performance with an effective friction factor while maintaining flow uniformity. This performance indicates that the flow dynamics induced by the groove lead to a stable core flow, eliminating the presence of secondary backflow vortices (see Fig. 8(b)). In fact, further increasing the groove height up to k/D_{int} =0.0795 does not significantly disrupt the hydraulic performance, as the groove intensifies lateral mixing without inducing excessive turbulence or instability.

In some instances, the use of spiral corrugated flexible pipes is necessitated for firefighting network applications due to design or structural constraints. It is important to note that opting for this alternative may result in a hydraulic performance disruption of approximately 60% when compared to conventional smooth pipes.

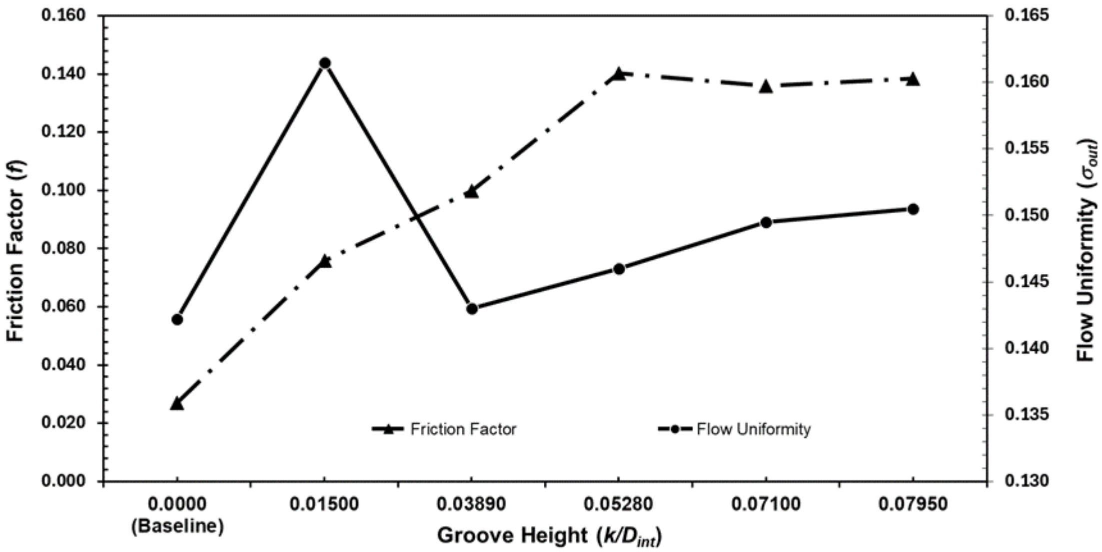


Fig. 11 *Effect of groove height (k/Dint) on hydraulic performance of spiral corrugated firefighting pipe*

Table 7 *Optimal groove height (k/Dint) of spiral corrugated firefighting pipe*

$\frac{k}{D_{int}}$	$f \times W$	$\frac{1}{f \times W}$	$\sigma_{out} \times W$	$\frac{1}{\sigma_{out} \times W}$	Total Score	Rank	Performance Disruption (%)
0.0000	0.0163	61.5006	0.0569	17.5809	79.0815	--------Baseline-------	
0.0150	0.0455	21.9587	0.0646	15.4799	37.4386	1	*52.6*
0.0389	0.0599	16.7001	0.0572	17.4948	34.1948	2	*56.8*
0.0528	0.0842	11.8793	0.0584	17.1350	29.0143	3	*63.3*
0.0710	0.0816	12.2549	0.0598	16.7336	28.9885	4	*63.4*
0.0795	0.0831	12.0337	0.0602	16.6113	28.6450	5	*63.8*

4. Conclusion

In conclusion, the study has numerically investigated the effect of groove height on the hydraulic performance of spiral corrugated firefighting pipes in comparison to conventional smooth pipes. The parametric analysis was conducted using the optimal groove configuration ultimately proposed. The following key findings have been validated, with uncertainties of less than ±5%. The findings indicate that the friction factor of spiral corrugated pipes is 336% higher than that of the smooth pipe due to the presence of secondary backflow vortices within the groove cavity. Despite the increase in friction losses, the flow uniformity of spiral corrugated pipes experiences only a slight disruption of 5.5% compared to the baseline. Furthermore, increasing the groove height beyond

k/D_{int} = 0.05280 has an insignificant effect on hydraulic performance, as the groove enhances lateral mixing without causing excessive turbulence or instability. Among the configurations, groove height (k/D_{int} =0.015) is regarded as the most optimal, yielding a balanced hydraulic performance with an effective friction factor while maintaining flow uniformity. Although spiral corrugated firefighting pipes may be necessary due to design or structural constraints, but they can result in hydraulic performance deficiencies of up to 60% compared to smooth pipes.

Acknowledgement

This research has been carried out under Industrial Grant Project (M134) provided by Taehwa Engineering Sdn Bhd. We also want to thank to the Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM) for providing facilities to conduct the work.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design****: N. Nordin, Gercham G., A. N. Mohammed;* ***data collection****: Gercham G., A. Hariri;* ***analysis and interpretation of results****: Gercham G., N. Nordin, M. S. Ramli;* ***draft manuscript preparation****: Gercham G., N. Nordin. All authors reviewed the results and approved the final version of the manuscript.*

Reference

[1] C. Yao, "Overview of Sprinkler Technology Research," in *Fire Safety Science*, 1997, pp. 93–110. https://doi.org/10.3801/IAFSS.FSS.5-93.

[2] K. Vishnoi, "Piping Layout for Fire Sprinkler System: An Overview," *International Journal of Engineering and Applied Sciences (IJEAS)*, vol. 4, no. 3, Mar. 2017, https://doi.org/10.31873/ijeas.4.3.15

[3] K. Moinuddin, I. Thomas, and S. Chea, "Estimating the Reliability of Sprinkler Systems in Australian High-Rise Office Buildings," in *Fire Safety Science*, 2008, pp. 515–526. https://doi.org/10.3801/IAFSS.FSS.9-515

[4] "Flexible Sprinkler Drops (for export) – DAEJIN SANUP Co." Accessed: Oct. 16, 2024. [Online]. Available: http://genie-systems.com/product/genie-drop/sp-joint

[5] H. Sun Ryou, O. Article, K. Bea Hong, and D. Woo Kim, "KSDS Numerical Study on the Effect of a Groove of D-type on Internal Flow and Pressure Drop in a Corrugated Pipe 주름관 내부 유동과 압력강하에 대한 D 형 그루브의 영향에 관한 수치해석," *J Korean Soc Disaster Secur*, vol. 14, no. 1, pp. 1–8, 2021, https://doi.org/10.21729/ksds.2021.14.1.1.

[6] B. Rajavel and M. G. Prasad, "Acoustics of Corrugated Pipes: A Review," 2013, *American Society of Mechanical Engineers (ASME)*. https://doi.org/10.1115/1.4025302.

[7] A. E. Perry, W. H. Schofield, and P. N. Joubert, "Rough Wall Turbulent Boundary Layers," *J Fluid Mech*, vol. 37, no. 2, pp. 383–413, Jun. 1969, https://doi.org/10.1017/S0022112069000619.

[8] K. B. Hong, D. W. Kim, J. Kwark, J. S. Nam, and H. S. Ryou, "Numerical Study on the Effect of the Pipe Groove Height and Pitch on the Flow Characteristics of Corrugated Pipe," *Energies (Basel)*, vol. 14, no. 9, May 2021, https://doi.org/10.3390/en14092614.

[9] R. Widiastuti, J. Zaini, M. A. Wibowo, and W. Caesarendra, "Indoor Thermal Performance Analysis of Vegetated Wall Based on CFD Simulation," *CFD Letters*, vol. 12, no. 5, pp. 82–90, 2020, https://doi.org/10.37934/cfdl.12.5.8290.

[10] S. A. Osman, A. J. Alimin, and V. S. Liong, "Optimum combustion chamber geometry for a compression ignition engine retrofitted to run using compressed natural gas (CNG)," in *Applied Mechanics and Materials*, 2013, pp. 552–556. https://doi.org/10.4028/www.scientific.net/AMM.315.552.

[11] O. M. M. Saufi, N. A. H. Roseman, I. Taib, N. F. Nasir, A. M. T. Ariffin, N. A. N. Salim, S. A. Osman, N. I. Darlis, and A. K. Kareem, "Flow Characteristics on Carotid Artery Bifurcation of Different Aneurysmal Morphology," *CFD Letters*, vol. 15, no. 2, pp. 25–40, Feb. 2023, https://doi.org/10.37934/cfdl.15.2.2540.

[12] M. S. Shuvo, T. H. Ruvo, and S. Saha, "Characteristics of Turbulent Forced Convective Nanofluid Flow and Heat Transfer in a 2D Axisymmetric Corrugated Pipe," *Thermal Science and Engineering Progress*, vol. 41, Jun. 2023, https://doi.org/10.1016/j.tsep.2023.101838.

[13] H. Stel, A. T. Franco, S. L. M. Junqueira, R. H. Erthal, R. Mendes, M. A. L. Gonalves, and E. M. Morales, "Turbulent Flow in D-type Corrugated Pipes: Flow Pattern and Friction Factor," *Journal of Fluids Engineering, Transactions of the ASME*, vol. 134, no. 12, 2012, https://doi.org/10.1115/1.4007899.

[14] J. I. Córcoles, J. F. Belmonte, A. E. Molina, and J. A. Almendros-Ibáñez, "Influence of Corrugation Shape on Heat Transfer Performance in Corrugated Tubes Using Numerical Simulations," *International Journal of Thermal Sciences*, vol. 137, pp. 262–275, Mar. 2019, https://doi.org/10.1016/j.ijthermalsci.2018.11.021.

[15] L. Y. Kashiwakura, C. E. R. S. C. Mendoza, C. L. Bassani, H. Stel, F. C. Vicencio, and R. E. M. Morales, "Pressure Drop Experimental Analysis for Horizontal Two-Phase Slug Flow in Corrugated Pipelines," in *Proceedings of the 23rd ABCM International Congress of Mechanical Engineering*, ABCM Brazilian Society of Mechanical Sciences and Engineering, 2015. https://doi.org/10.20906/cps/cob-2015-0824.

[16] S. Zhu, J. Wang, and J. Xie, "Numerical Investigation of the Heat Transfer Characteristics of R290 Flow Boiling in Corrugated Tubes with Different Internal Corrugated Structures," *Mathematics*, vol. 9, no. 22, Nov. 2021, https://doi.org/10.3390/math9222969.

[17] S. Pethkool, S. Eiamsa-ard, S. Kwankaomeng, and P. Promvonge, "Turbulent Heat Transfer Enhancement in a Heat Exchanger Using Helically Corrugated Tube," *International Communications in Heat and Mass Transfer*, vol. 38, no. 3, pp. 340–347, Mar. 2011, https://doi.org/10.1016/j.icheatmasstransfer.2010.11.014.

[18] H. S. de Azevedo, M. M. Franco, R. E. M Morales, A. T. Franco, S. L. M Junqueira, and R. H. Erthal, "Flow Pattern and Friction Measurements of Turbulent Flow in Corrugated Pipes."

[19] L. Xiuzhen, L. Shijie, M. Xuan, S. Zhaoyang, T. Guo, X Yifan, and Z. Dongsheng, "Investigation on Convection Heat Transfer Augment in Spirally Corrugated Pipe," *Energies (Basel)*, vol. 16, no. 3, Feb. 2023, https://doi.org/10.3390/en16031063.

[20] N. N *et al.*, "Assessment of Turbulence Model Performance Adopted Near Wall Treatment for a Sharp 90° 3-D Turning Diffuser," Springer Nature Singapore Pte Ltd., 2017, pp. 259–273. https://doi.org/10.1007/978-981-10-6463-0_23.

[21] N. Nordin, Z. A. A. Karim, S. Othman, and R. V. R, "The Performance of Turning Diffusers at Various Inlet Conditions," in *Applied Mechanics and Materials*, 2013, pp. 465–466. 597–602, Dec. 2013, https://doi.org/10.4028/www.scientific.net/AMM.465-466.597

[22] G. G. S. X, "Experimental Investigation of Flow & Pressure Performance of Enhanced DesigFire-Fighting," in Faculty of Mechanical and Manufacturing Engineering. Bachelor's Degree Project II in Mechanical Engineering, Batu Pahat: Universiti Tun Hussein Onn, 2024.