International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 16 (2017) pp. 5604-5609
© Research India Publications. http://www.ripublication.com

Numerical Study of 3-Dimensional Wall Jet on Curved Surfaces

S.V.H.Nagendra[1], Prasant Nanda[2] and DVS Bhagavanulu[3]

[1]*Department of Mechanical Engineering, Veer Surendra Sai University of Technology, Burla, Odissha, India.*
Orchid id: 0000-0001-7719-8930

[2]*Dean Training and Placement, Veer Surendra Sai University of Technology, Burla, Odissha, India.*
Orchid id: 0000-0001-8922-1149

[3]*Department of Civil Engineering, Sri Vidyanikethan Engineering College, Tirupati, Andhra Pradesh, India.*
Orchid id: 0000-0001-7631-010X

Abstract

Experimental and Numerical Investigation has been carried out on three-dimensional wall jet developing on curved surfaces. The jet impinges on convex and concave cylindrical surfaces and the aspect ratio of the orifice is unity. The mean flow velocity profiles are measured in longitudinal and spanwise direction and compared with the results of plane wall jet. The flow parameters included in the present study are decay of maximum velocity, growth of half width and variation of curvature parameter. It is observed from the studies that the decay of maximum velocity is faster in convex surface compared to both concave and plane surfaces. Also, it is found that the growth on concave surface slower compared to plane surface. The growth of half width is increased over convex surface and decreased over concave surface. The curvature parameter decreases with the decrease of half width on concave surface where as the curvature parameter increases with the increase of half width on convex surface.

Keyword: Wall jet; CFD; Curved surface; Mean flow characteristics

INTRODUCTION

Fluid flowing on one sided wall configuration is often called as wall jet. When the jet impinges on the surface tangentially, the wall jet formed is plane wall jet and sometimes it is often called as attached jet. Initially reported work on a wall jet was conducted by Forthmann (1934). An extensive overview of experimental work done until 1980 is given by Launder and Rodi (1981). An overview of numerical work until the beginning of the 1980s is presented by Launder and Rodi (1983). Studies on moderate and strong curved surfaces were given by Gibson et al. (1984) and Kobayashi and Fujisawa (1983). Similarly, wall jet over a convex surface was also studied by Alcaraz et al. (1976) and Wilson and Goldstein (1976), while Neuendorf and Wygnanski (1999) studied the effect of surface curvature on the development of a two-dimensional wall jet around a circular cylinder.

In the current investigation, the mean flow parameters of three dimensional wall jet were studied. The mean flow velocity profiles were measured in longitudinal and span wise directions. The other mean flow parameter like decay of maximum velocity and half width growth are also investigated and the effect of curvature parameter in the radial decay region on the growth of half width are compared both for convex and concave surfaces. The fluid (air) is issued from an orifice having h/d ratio equals to one as shown in Figure1. The convex and concave surfaces are fabricated with an initial straight portion of twenty times the width of the orifice and later a constant radius of curvature of wall followed. Wall jet formed on two different walls having constant radius of curvature 3m and 1.5 m respectively. The same radius of curvature is maintained for both convex and concave surfaces. The measurements are taken up to 40 times of width of the orifice and also measurements are taken on plane surface for the purpose of comparison.

The computational modeling is done using the commercial CFD code Fluent 13.0. The Two equation turbulence model is used to find the turbulence parameters and later the Reynold Stress closure model (RSM) variant(Launder Riece Rodi LRR-IP) is used . The meshing of the model is done using unstructured grid method with tetrahedral element. Second order advection scheme is considered for solving the continuity, momentum and Reynold stress equations with 1e-4 convergence criteria. Reynolds number of the model is about 1.46×10^6. The initial boundary condition for the flow is defined in the terms of turbulence intensity and hydraulic diameter i.e. 5% and 0.034 m.

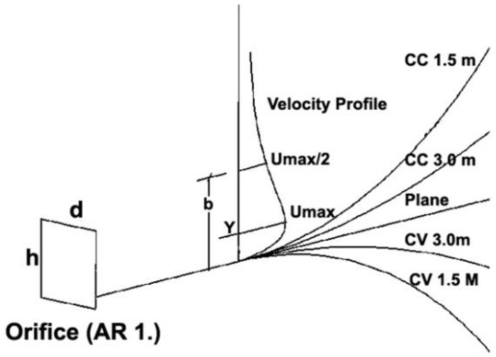

Figure 1: Wall jet Configuration for Convex, Concave and Plane Surface

NUMERICAL ANALYSIS

A. The Governing Equations

Reynolds Stress model (RSM)

The exact transport equations for the transport of the Reynolds stresses $\rho u'_i u_j'$ may be written as follows

$$\underbrace{\frac{\partial}{\partial t}\left(\rho\overline{u_i'u_j'}\right)} + \underbrace{\frac{\partial}{\partial x_k}\left(\rho u_k\overline{u_i'u_j'}\right)}$$

Local Time Derivative $\quad$ *C_{ij} =Convection*

$$= \underbrace{-\frac{\partial}{\partial x_k}\left[\rho\overline{u_i'u_j'u_k'} + \overline{p'\left(\delta_{kj}u_i' + \delta_{ik}u_j'\right)}\right]}$$

$D_{T,ij}$ = Turbulent Diffusion $+ \underbrace{\frac{\partial}{\partial x_k}\left[\mu\frac{\partial}{\partial x_k}\left(\overline{u_j'u_k'}\right)\right]}$

$D_{L,ij}$=*Molecular Diffusion*

$$-\underbrace{\rho\left(\frac{\overline{u_i'u_k'}(\partial u_j)}{\partial x_k} + \frac{\overline{u_j'u_k'}(\partial u_i)}{\partial x_k}\right)}$$

P_{ij} = Stress Production

$$-\underbrace{\rho\beta\left(g_i\overline{u_j^{\prime}}\theta + g_j\overline{u_i^{\prime}}\theta\right)} + \underbrace{\overline{p'\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right)}}$$

G_{ij}= Buoyancy Production $\quad$ *Φ_{ij} = Pressure Strain*

$$-\underbrace{2\mu\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}} -$$

E_{ij}= Dissipation $\quad$ *F_{ij} Production by System Rotation*

+ *S_{user} (User Term)* . (1)

The terms in these exact equations such as C_{ij}, D_{Lij}, P_{ij}, and F_{ij} do not require any modeling. However, D_{Tij}, G_{ij}, φ_{ij} and ϵ_{ij} need to be modeled to close the equations. D_{Tij} is diffusivity term is modeled using gradient diffusivity model by Daly and Harlow,

$$D_{T,ij} = C_s\ \partial/\partial x_k\left(\frac{\rho k\overline{u'_k u'_l}}{\varepsilon}\cdot\frac{\partial\overline{u'_i u'_j}}{\partial x_l}\right) \qquad (2)$$

D_{Tij} =*Diffusivity Term*

G_{ij} is the buoyancy term which is neglected, φ_{ij} is the pressure strain term modeled using return isotropy, rapid pressure strain and wall reflection term where as ϵ_{ij} dissipation tensor term is modeled as

$$\in ij = \frac{2}{3}\delta ij(\rho\varepsilon + Ym) \qquad (3)$$

$\in ij$ = *Dissipation Tensor*

GRID DEPENDENCY

The three dimensional computational domain has been tested for grid dependency for three mesh models $5x10^5$, $7.5x10^5$ and $11.5x10^5$ elements.

The velocity factor u/u_{max} at 20 times of d has been measured and it has been found out that there is no significant change in the variable after $7.5x10^5$ elements. So the grid size taken for the both the domain is $7.5x10^5$ approx.

EXPERIMENTAL SETUP AND INSTRUMENTATION

The experimental setup consists of a centrifugal blower, traverse table, digital micro-manometer and total pressure probe to measure the velocity values at different stations on the surface of investigation. The measurements are taken both in the longitudinal as well as spanwise directions. The calibration of the total pressure probe is done using a standard probe of 99.2% confidence in the laboratory. The tunnel is calibrated for maximum turbulence intensity below 5%.

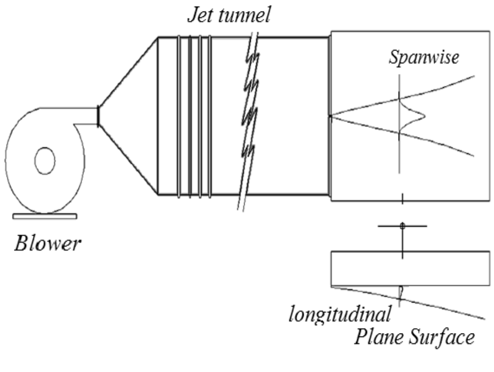

Figure 2: Experimental Setup with plane surface

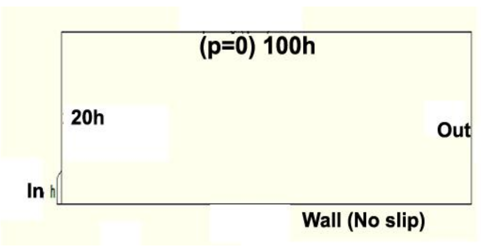

Figure 3: Shows computational domain

RESULTS AND DISCUSSION

A. Velocity distribution

Figures 4 and 5 show the velocity distribution contours both on convex and concave surfaces. It can be seen that the in both the cases the potential core region is well predicted for both the surfaces by the RSM model. The free jet velocity contour for the surface also shows conformity with the existing understanding.

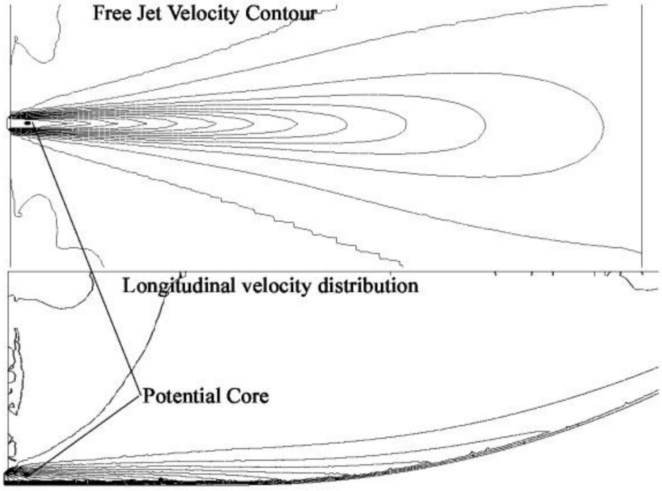

Figure 4: Contour plot showing velocity distribution on concave surface.

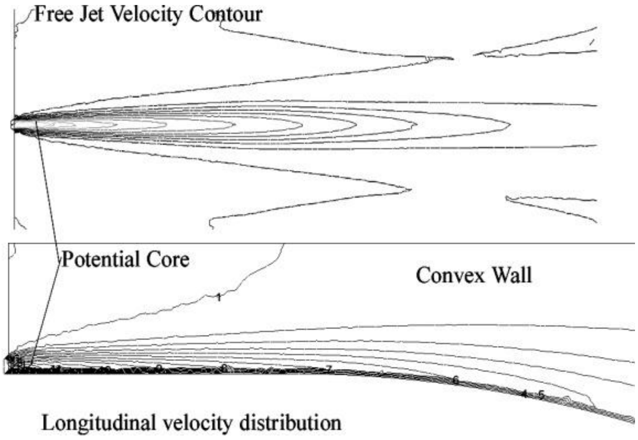

Figure 5: Contour plot showing velocity distribution on convex surface.

B. Mean Velocity profiles

Figures 6, 7 and 8 shows the mean velocity profiles on convex, concave and plane surfaces at different stations i.e. 20d, 30d and 40d. The shape of the velocity profile matches the trend given by Glauret. The point of maximum velocity shows same on both convex (3m and 1.5m) and concave (3m and 1.5m) surfaces. The CFD results shows higher values but again same for convex and concave surface that is 0.25 and 0.3 . Figure 9 shows the velocity profile drawn at 20d in the spanwise direction for all the surfaces and it can be seen that it obeys the free jet configuration, but there is slight variation in CFD results at $z/z_{m/2}$is greater than 1.2.

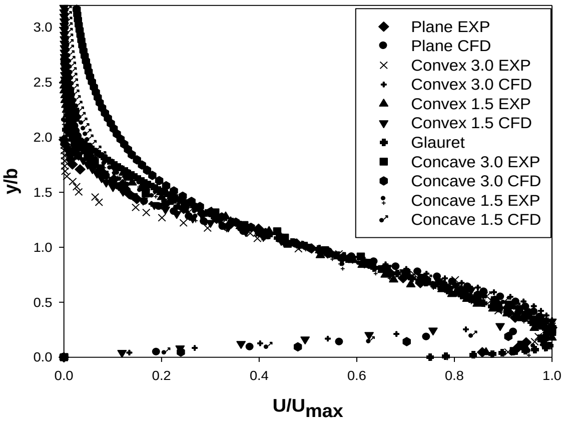

Figure 6: Mean velocity profiles at 20 d for all the surfaces in the longitudinal direction

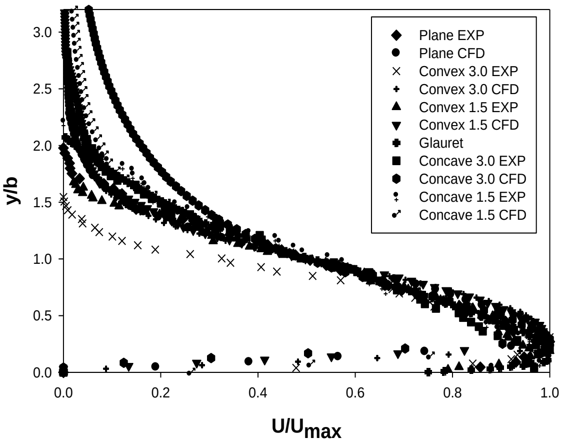

Figure 7: Mean Velocity Profiles at 30 d for all the surfaces in the longitudinal direction

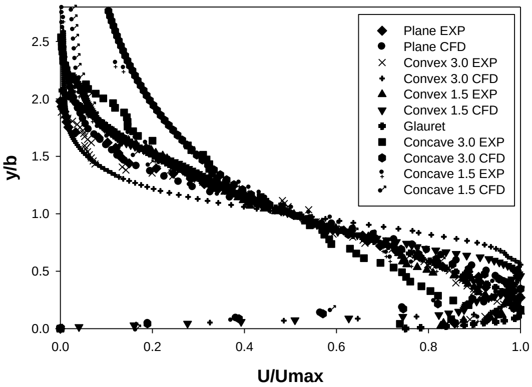

Figure 8: Mean Velocity Profiles at 40 d for all the surfaces in the longitudinal direction

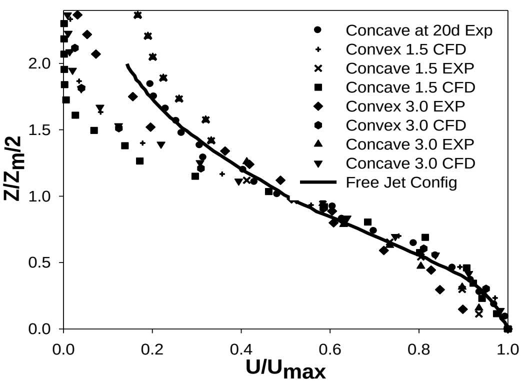

Figure 9: Mean velocity profiles in the spanwise direction at 20d for all the surfaces

C. Decay of Maximum Velocity

The decay of maximum velocity for a wall jet is usually represented by power law form i.e.,

$$(U_m/U_j) \propto (x/h)^n \qquad (4)$$

Fig 10 shows the decay of maximum velocity for plane, convex (3m &1.5m) and concave (3m & 1.5m). The experimental results shows that the decay of maximum velocity is faster in case of convex when compared to plane and concave surfaces, and the growth over the concave surface (3m & 1.5m) shows slower than plane and convex. Similar trend can be seen in numerical results. The value of exponent ‘n’ is shown in table 1 for both experimental and numerical results.

Table 1: Decay exponent’s values for all the surfaces.

Surface Type	n in RD (Exp)	n in RD (CFD)
Plane Surface	-1.36	-0.4
Convex 3.0 m	-1.82	-0.75
Convex 1.5 m	-1.45	-0.97
Concave 3.0 m	-0.94	-0.74
Concave 1.5 m	-1.1	-1.02

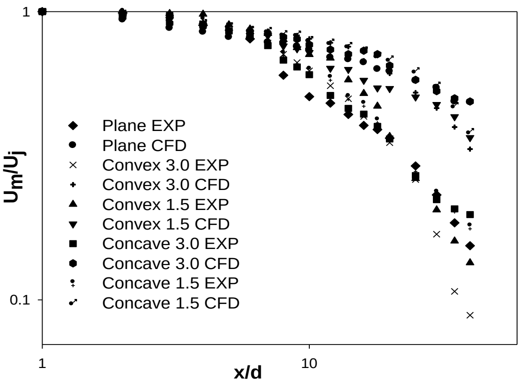

Figure 10: Decay of Maximum Velocity in the longitudinal direction for all surfaces

D. Growth of Half Width

Figure 11 shows the experimental and CFD results of growth of half width for plane, convex and concave surfaces. The experimental results shows growth of half width is higher on convex surface when compared to plane surface results. It is also observed that the growth of half width is increased with the decrease in the radius of curvature for convex surface. The existence of rolling vortices to expand further in the outer region of wall jet over convex surface a thus increases the growth of half width. In case of concave surface, the growth of half width is decreased when compared to plane surface, in the radial decay region. But a different trend is observed on concave surface i.e., the growth of half width is decreased with the decrease in radius of curvature. The reason is due to the formation of longitudinal rolling vortices on concave surface. The same behavior is seen in numerical results.

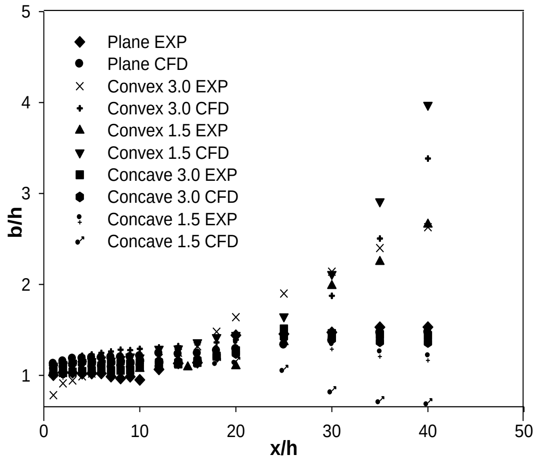

Figure 11: Growth of Half Width on all the surfaces

E. Effect of Curvature parameter on half width growth

Figure 12 shows the effect of curvature parameter in the growth of half width for convex and concave surfaces. The results show that in case of convex surface with the increase in curvature parameter b/R the growth of half width also increased. As the radius of curvature of the surface reduces to 1.5 m from 3 m the curvature parameter shows further increase and in return the half width is also increased.

In case of concave surface in the radial decay region, the curvature parameter b/R and the growth half width b/h is decreased with the decrease in radius of curvature.

The numerical results showed good agreement with the experimental results.

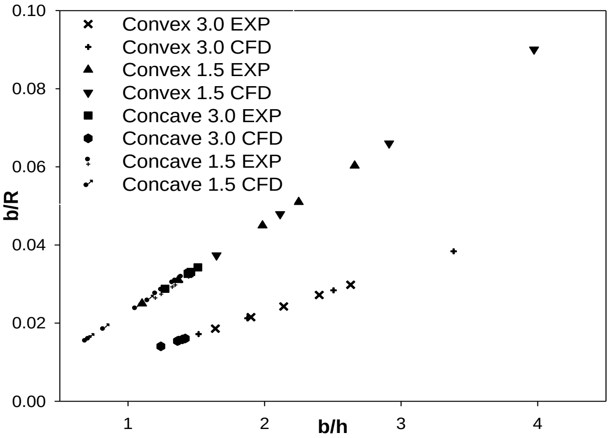

Figure 12: Variation of Curvature parameter for all the Convex and Concave surface

CONCLUDING REMARKS

The mean velocity profiles showed good agreement with the experimental results and also followed the trend of Glauret. There is no change in the shape of the velocity profiles on curved surfaces.

The Decay of maximum velocity is faster on Convex surface and slower on concave surface compared to the decay over Plane surface.

The growth of half width is increased over convex surface and decreased over concave surface. The growth of half width is increased with the decrease in radius of curvature. But in the case of concave surface the growth of half width is decreased with the decrease in radius of curvature which is due to the centrifugal stability over concave surface.

The increase in the growth of half width on convex surface is attributed to centrifugal instability in the outer region of the wall jet. On concave surface the secondary flow is attached to primary flow and shifts toward the flow. Thus the growth of half width is reduced over concave surface.

The turbulent kinetic energy reduces with the increase in radius of curvature on convex surface and whereas the kinetic energy is increased with the reduction in radius of curvature. Also, it is observed that the kinetic energy is more on the curved surfaces when compared to plane surface. The kinetic energy over concave surface is more than the convex surface for the same radius of curvature. The reverse phenomenon occurs in the case of eddy dissipation i.e., on convex surface the eddy dissipation increase with the reduction in radius of curvature and on the concave surface the eddy dissipation reduces with the increase in radius of curvature.

ACKNOWLEDGEMENT

This paper results from the first author’s PhD research work through the support of All India Council of Technical Education India, Delhi Research Promotion Scheme grant.

REFERENCES

[1] Alcaraz, E., Charnay, G. and Mathieu, J. "Measurements in wall jet over a convex surface", Physics of Fluids, Vol. 20, 1977 , 203-210.

[2] Ch. Heschl, W. Sanz and P. Klanatsky "Implementation and comparison of different turbulence models for three dimensional wall jets with FLUENT" CFD Forum, Bad Nauheim. 2005.

[3] Forthman, E. “Turbulent jet expansion", Ingenieur-Arch. Vol. 5, 1934 , pp. 42.

[4] Fujisawa, N. and Shirai, H. "Theoretical and experimental studies of a turbulent wall jet along a strongly concaved surface", Trans. Japan Soc. Aero. Sciences, Vol. 30, 1987 , pp. 26-37.

[5] Fujisawa, N. and Shirai, H. "Theoretical and experimental studies of turbulent wall jet along a strongly concaved surface", Transactions of Japan Society for Aero Space Sciences, Vol. 30, 1986 , pp. 162-172.

[6] Glauert, M.B. “The wall jet”, J. Fluid Mech., Vol. 1, 1956 , pp. 625-643.

[7] Guitton, D.E. and Newman, B.G. “Self-preserving turbulent wall jets over convex surfaces”, J. Fluid Mech., Vol. 81, 1977 , pp. 155-185.

[8] Giles, J.A., Hays, A.P. and Sawyer, R.A. “Turbulent wall jets on logarithmic spiral surfaces”, Aero. Quarterly, Vol. 17, 1966 , pp. 201-215.

[9] Gibson, M.M. and Younis, B.A. "Modeling of curved turbulent wall jet", AIAA, Vol. 20, 1982 , pp. 1707-1712.

[10] J. G. Eriksson, R. I. Karlsson and J. Persson "An Experimental Study of a Two-Dimensional Plane Turbulent Wall Jet"Experiments in Fluids 25 1998, pp. 50-60

[11] Kobayashi, R. and Fujisawa, N. "Curvature effects on two-dimensional wall jet along concave surfaces", Bull. JSME, Vol. 26, 1983 , pp. 2074-2080.

[12] Launder, B.E. and Rodi, W. "The turbulent wall jet", Progress in Aerospace Sci, Vol. 19, 1981 , pp. 81-128.

[13] Launder, B.E. & Rodi, W., The turbulent wall jet", Annual Review Fluid Mech., Vol. 15, 1983 , pp. 429-435.

[14] Launder, Reece And Rodi "Progress in the development of a Reynolds-stress turbulence closure", Journal of Fluid Mechanics, Vol. 68 3 1975 , pp. 537-566.

[15] Neuendorf, R. and Wygnanski, I. “On a turbulent wall jet flowing over a circular cylinder”, J Fluid Mech., Vol. 381, 1999 , pp.. 1-25

[16] Rajaratnam, N., Turbulent Jets, Elsevier, Amsterdam, 1976

[17] Wilson, D.J. and Goldstein, R.J., “Turbulent jets with cylindrical stream wise surface curvature”, J. Fluids Engg., Trans. ASME, Vol. 98, 1976 , pp. 550-557.

[18] S. V. H. Nagendra,D. V. S. Bhagavanulu and Nanda Prasant "Computational Study of Three Dimensional Wall Jet on Concave Surface "Fluid Mechanics and Fluid Power Contemporary Research, Vol 1,2016, pp. 529-538.