VOL. 10, NO. 12, JULY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

THE MEREDITH RAMJET: AN EFFICIENT WAY TO RECOVER THE HEAT WASTED IN PISTON ENGINE COOLING

Luca Piancastelli[1], Leonardo Frizziero[1] and Giampiero Donnici[2]
[1]Department of Industrial Engineering, Alma Mater Studiorum University of Bologna, Viale Risorgimento, Bologna, Italy
[2]Innovation Center of Design Srl, via Laura Bassi, Bologna, Italy
E-Mail: leonardo.frizziero@unibo.it

ABSTRACT

Piston engines with power up to 1000HP (735.5 kW) are becoming popular in the aeronautical field for the high efficiency and the possibility to work with Diesel, jp4 and jp8 fuels up to altitudes up to 20,000m (65,000 ft). This paper updates a secondary advantage of piston engines: the Meredith effect. The Meredith duct is a ramjet powered by the heat wasted in cooling. In this way the efficiency of the original piston engine that can be higher than 50% which is the normal in common rail diesel engines. Even if the efficiency of this ramjet is lower than 30%, an accurate Design of this secondary engine can add a significant amount of thrust to the fan or the propeller powered by the piston engine. This effect, well known since the beginning of WWII, is being thoroughly analysed in this paper with regard of the efficiency. Previous papers introduced and a new radiator, with wing section tubes. As it will be seen the main design variable for the Meredith ramjet it the air temperature increase. This paper demonstrates that it is not convenient to increase this temperature over 200°C for aircrafts flying at about 600km/h@6000m (~330knots@20,000ft). The in-wing duct appears to be slightly better than the in-fuselage or the in-nacelle ones.

Keywords: piston engine cooling

INTRODUCTION

The Meredith ramjet development starts from Report no. 1683 (by F.W. Meredith of the Royal Aircraft Establishment in Farnborough, England, published in 1935) and by the follow-up article by R.S. Capon also of the RAE in 1935 which elaborated on the effect first studied by Meredith. Both of the authors assumed a fully enclosed ramjet that used the cooling radiator to energize the stream air. The design of the duct proved to be non-trivial and resulted in the first duct to be held away from the fuselage to keep the opening out of the turbulent fuselage boundary layer, which created vibration problems with flush openings. The conclusion, as stated in the Capon's article is as follows: "The Meredith Effect involved preventing excessive cooling air from flowing through the radiator at high speed by partly closing the outlet and developing a pressure behind the radiator, which, being less than on the forward face, created a jet of exhaust air. As with any pressure jet, this put a forward reaction force on the airplane, which partly offset the drag of the radiator. The temperature increase in the exhaust air (from the air being heated by the radiator) expanded its volume and augmented this force appreciably because the size of the exit opening could be somewhat larger with the same internal pressure."

As in any ramjet Meredith that to obtain this result the radiator must be installed in a duct (Figure-1).

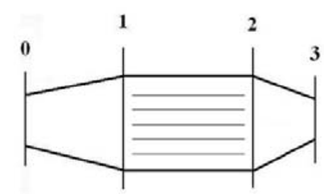

Figure-1. Meredith's duct (skeme).

Figure-1 shows a diffuser from section 0 to section 1, in which the airflow slows down and pressure increases. The radiator (section 1-2) transfers energy to the cold air stream and, consequently, the air speed increases. In this way, kinetic energy is obtained from heat. The low velocity values reduce the radiator pressure drop (drag). Finally, a nozzle accelerates the airflow for optimum propulsion efficiency (section 2 to 3).

Several examples of application of the Meredith duct are available from almost every liquid cooled piston engine installation. In this paper, we will compare two different approaches. The fuselage duct of the Mustang P-51D-K with is compared with the one of the Bf 109 E-K with a wing embedded duct and wing-shaped-tube radiator. With the introduction of the E model powered by the powerful DB601 engine, a new cooling system was introduced. The liquid cooling system was serviced by two equal- radiators which were almost completely recessed within the wings (blue circles in Figures 2 and 3). De Havilland on the Mosquito also designed a frontal-intake in-wing-duct solution. The concept is to put the intake in a

VOL. 10, NO. 12, JULY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

relatively high pressure clean area and design the exhaust in a more turbulent part of the aircraft. In the BF109 and the Mosquito, the hot air contributed to the lift at slow speed with the flaps down.

Figure-2. Bf 109 E-K Meredith's duct intake.

Figure-3. Meredith duct intake (Bf 109 E-K).

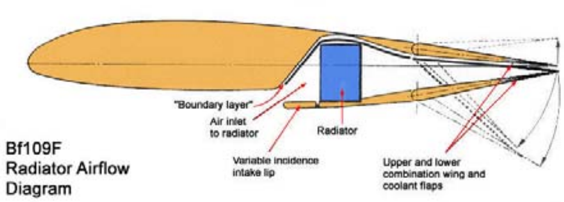

Figure-4. The Bf 109F-K duct.

In the Bf109 the cooling air would enter a simple, low aspect ratio, box-shaped intake and then was routed to the radiator through an extremely short diffuser. A small flaps assembly at the aft edge of the radiator bath operates the regulation of the nozzle geometry and varies the hot air jet direction. In the F version a new boundary layer duct allows a continual airflow to pass through the airfoil above the radiator ducting and exit from the trailing edge of the upper split flap. The Bf109F the radiator duct was designed for maximum speed at nominal altitude. The radiators of bombers were optimized for cruise. In both cases, a 20% over-dimensioning was included for climb and warm weather flight. F1 cars also use the Meredith duct (Figure-5).

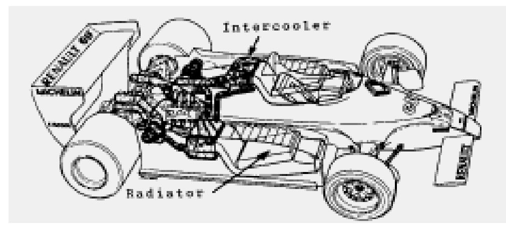

Figure-5. F1 Meredith duct for the cooling radiators (liquid and oil), Renault F1, 1982.

Figure-6. "P51 style",_1996 Ferrari F1, Meredith duct air intake.

In this case, a thin, flat tubes, highly inclined radiator is used. This configuration is particularly favorable at the low speeds of F1 racing (below 83 m/s). In this way, the heat exchanger works in a mix of cross-flow and counter current. A very short streamline diffuser completes the Meredith duct. The two exhausts work as ejectors at the duct nozzles. This configuration also avoids the intake vortex typical of short diffusers. On the contrary, with short diffusers and thick radiators the guiding flap is strictly necessary (Figure-7).

ARPN Journal of Engineering and Applied Sciences

Figure-7. Re 2005 cooling duct with the flap in the extremely short diffuser.

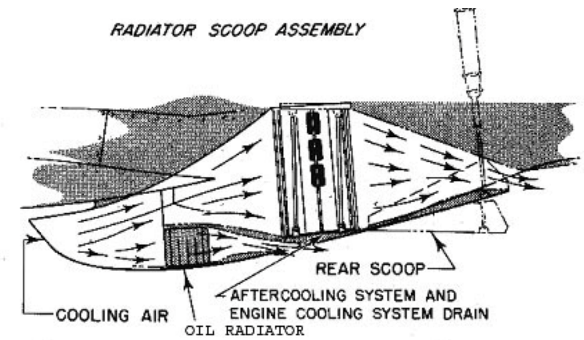

Figure-8. P51D Meredith's cooling duct.

Figure-9. P51D-K cooling duct intake with boundary layer diverter.

Figure-10. P51D-K cooling air intake shape optimized for high angle of attack (AOA) flight.

The Mustang P-51D is famous for being considered the faster WWII Allied fighter. Two technological innovations, the laminar-profile wings and the Meredith effect radiator supported this claim. The ducted radiator is located under the pilot (rounded in red in Figures 9 and 10). The oil radiator was separated from the main radiator, which includes the engine and the aftercooling system radiators (Figure-8), and had independent engine sections. In the H model, a single duct was obtained by using a thin oil and aftercooler radiator in front of the engine coolant one. The airflow regulation was guaranteed by a flap system mounted at the end of the duct. A supercharged Packard Merlin with about 1700 HP powered this aircraft and the cooling system was able to guarantee a estimated thrust of about 2,000 N at top speed (195m/s@10,000m).

An example of traditional design of the Meredith jet engine

In this starting example the power (heat flow) to be transformed in thrust is Q_{TOT} = 2000 kW.

The cruise speed is 153 m/s@5,000m ISA+0°. The intake area S can be calculated with equation (1) with the assumption that T2-T1=75°C (see Figure-1).

$$S = Q / (\rho \, V \, C_{pa} \, \Delta T) = 0.1848 \text{ m}^2 \quad (1)$$

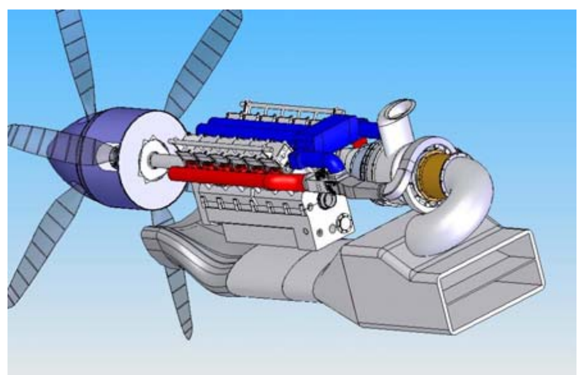

Figure-11. Power pack with Meredith duct.

If the engine is installed as a power-pack in front of the wing main spar it is possible to have a Meredith duct similar to one of Figure-11 with “shark mouth” air intake [xxx]. The propeller increases the total pressure in front of the radiator approximately 7% of the free-stream dynamic pressure at cruise speed. However, there is an effect of propeller operation on total pressure distribution at the face of the radiator. The core of high pressures is concentrated in the upper part of the radiator duct. At the bottom of the duct lip, the critical speed of the section varies slightly and irregularly with propeller operation. In the forward underslung radiator, the ratio between the distance from the lower lip of the air intake to the

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

propeller axis and the propeller radius should be kept under 0.48 [xxx].

In the diffuser, a good value of the semi-angle opening of the duct of about 7°. Actually, the presence of the diffuser causes an increase in the radiator losses due to the deviation of the airflow in front of the radiator.

The streamline diffuser minimizes both the internal losses and the rise of the drag coefficient of the radiator due to the diffuser presence. In our case, the use of a streamline diffuser can decrease the losses of about 20%. The NACA 0014 tube geometry minimizes the drag coefficient of the radiator core (Figure-12). This choice is similar to the one adopted in the Bf109F-K.

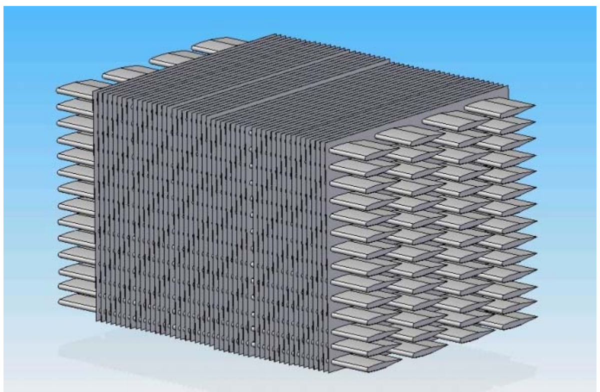

Figure-12. radiator core.

With this profile we conserve the same flow coefficient through the radiator of the flat tube radiator, and also the overall thermal efficiency. Therefore, the only change made is the reduction of the drag coefficient. In this way, it is possible to reduce of 6% the pressure drop of the equivalent flat tube radiator. The nozzle has negligible distributed and concentrated losses. However, it has an important on the drag coefficient of the core radiator.

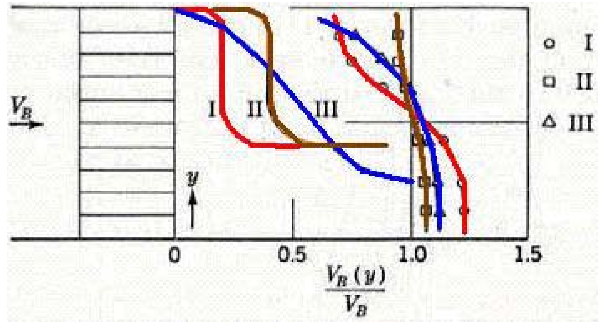

Figure-13. Nozzle velocity.

Figure-13 shows that the brown profile (II) has a more constant distribution of the air velocity exiting from the radiator. That means that the most important parameter in dimensioning the nozzle is the distance between the beginning of the nozzle and the radiator core. The nozzle should have a variable geometry in order to optimize thrust and cooling at different speeds and AOA (Angle Of Attack). The result is a theoretical thrust force of about 2, 500 N. The external drag of the nacelle due to the presence of the duct is not included in this value.

Energy evaluations

The theoretical overall efficiency of the duct is then (2):

$$\eta_t = \frac{P_0}{P_{available}} = \frac{\frac{\dot{m}}{2}\left(V_{outlet}^2 - V_{inlet}^2\right)}{Q} = 0.29 \qquad (2)$$

The different conditions of the fluid in the optimized duct are summarized in Table-1.

Table-1. Optimized Meredith duct data.

# section (see Figure-1)	**Pressure** (Pa)	**Velocity** (m/s)	**Temperature** (K)	**Equivalent enthalpy** (kJ/kg)
0	54019.9	152.9	255.65	267.3
1	61644.2	30.6	263.15	263.6
2	54185	44.8	338.15	339.15
3	54019.9	296	276.9	336

The radiator pressure drop can be extimated with equation 3 and varies with the square of the velocity and linearly with the radiator thickness b:

$$\Delta p = \left|p_2 - p_1\right| = \xi\, b\, V^2 = 07459[Pa] \qquad (3)$$

The radiator temperature increment goes linearly with the radiator thickness. So higher T2-T1 implies longer duct to recover more pressure in the diffuser to compensate the higher pressure drop. Since the diffuser

ARPN Journal of Engineering and Applied Sciences

length is about 3/4 of the overall duct length, weight and drag are highly affected by this factor.

It is then possible to evaluate other possible configurations with different values of T2-T1.

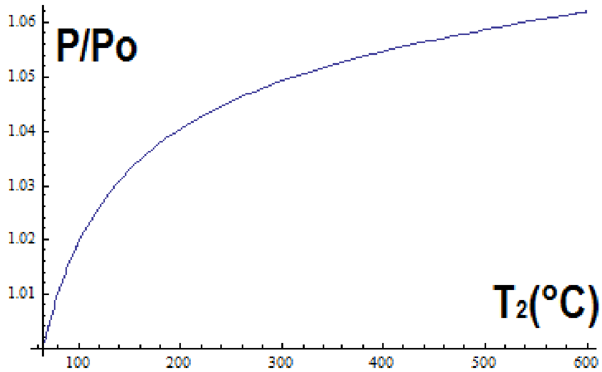

Figure-14. Power ratio P/P0 increment withT2.

From Figure-14 it is possible to see that it is not convenient to rise T2 over 200°C, since the power P increment (or net Thrust) is negligible. Far more important is to keep the aerodynamic drag of the Meredith duct as small as possible. From this point of view, the solution shown in Figure-11 with its bulky duct is far from ideal. The best designs are again the ones from WWII, especially the in-wing solutions like the ones of the BF109 and the Mosquito. In this case, thick and low aspect ratio radiators add very little drag to the wing. The flaps divert downwards the nozzle hot jet at take off adding lift. In levelled flight, the Meredith ramjet trust increases the propeller/fan one.

CONCLUSIONS

The additional thrust of the cooling system further increases the interest for piston engines propulsion in aeronautical field. In fact, due to the Meredith effect, it has been possible to eliminate the radiator drag and to increase the total thrust of the power-pack. Therefore, Meredith ramjet improves the total available thrust and reduces fuel consumption. Both under-fuselage/under nacelle and in-wing configurations were analyzed. In order to reduce the external drag of the duct and to improve lift at take off the in-wing solution with its low aspect ratio radiators seems to be the best choice. The possibility of long high temperature duct of the under-fuselage/under nacelle does not give significant improvements in term of efficiency and thrust. Moreover, higher coolant temperature and thicker radiators increase substantially the overall weight of the Meredith ramjet. Thicker radiators also require longer diffusers and additional duct drag.

REFERENCES

[1] W.J. Nelson, K.R. Czarnecki and R.D. Harrington. 1946. NACA report L-115 Full-scale wind-tunnel investigation of forward underslung cooling-air ducts. December 23rd.

[2] L. Piancastelli, L. Frizziero, G. Zanuccoli, N.E. Daidzic, I. Rocchi. 2013. A comparison between CFRP and 2195-FSW for aircraft structural designs. International Journal of Heat and Technology. 31(1): 17-24.

[3] L. Piancastelli, L. Frizziero, N.E. Daidzic, I. Rocchi. 2013. Analysis of automotive diesel conversions with KERS for future aerospace applications. International Journal of Heat and Technology. 31(1): 143-154.

[4] L. Piancastelli, L. Frizziero, I. Rocchi. 2012. An innovative method to speed up the finite element analysis of critical engine components. International Journal of Heat and Technology. 30(2): 127-132.

[5] L. Piancastelli, L. Frizziero, I. Rocchi. 2012. Feasible optimum design of a turbocompound Diesel Brayton cycle for diesel-turbo-fan aircraft propulsion. International Journal of Heat and Technology. 30(2): 121-126.

[6] L. Piancastelli, L. Frizziero, S. Marcoppido, A. Donnarumma, E. Pezzuti. 2011. Fuzzy control system for recovering direction after spinning. International Journal of Heat and Technology. 29(2): 87-93.

[7] L. Piancastelli, L. Frizziero, S. Marcoppido, A. Donnarumma, E. Pezzuti. 2011. Active antiskid system for handling improvement in motorbikes controlled by fuzzy logic. International Journal of Heat and Technology. 29(2): 95-101.

[8] L. Piancastelli, L. Frizziero, E. Morganti, E. Pezzuti: 2012. Method for evaluating the durability of aircraft piston engines. Published by Walailak Journal of Science and Technology. The Walailak Journal of Science and Technology, Institute of Research and Development, Walailak University, ISSN: 1686-3933, Thasala, Nakhon Si Thammarat 80161, 9(4): 425-431, Thailand.

[9] L. Piancastelli, L. Frizziero, E. Morganti, A. Canaparo: 2012. Embodiment of an innovative system design in a sportscar factory. Published by Pushpa Publishing House. Far East Journal of Electronics and

Communications”, ISSN: 0973-7006, 9(2): 69-98, Allahabad, India.

[10] L. Piancastelli, L. Frizziero, E. Morganti, A. Canaparo: 2012. The Electronic Stability Program controlled by a Fuzzy Algorithm tuned for tyre burst issues. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006, 9(1): 49-68, Allahabad, India.

[11] L. Piancastelli, L. Frizziero, I. Rocchi, G. Zanuccoli, N.E. Daidzic: 2013. The "C-triplex" approach to design of CFRP transport-category airplane structures. International Journal of Heat and Technology, ISSN 0392-8764, 31(2): 51-59.

[12] L. Frizziero, I. Rocchi: 2013. New finite element analysis approach. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006, 11(2): 85-100, Allahabad, India.

[13] L. Piancastelli, L. Frizziero, E. Pezzuti. 2014. Aircraft diesel engines controlled by fuzzy logic. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(1): 30-34, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[14] L. Piancastelli, L. Frizziero, E. Pezzuti. 2014. Kers applications to aerospace diesel propulsion. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(5): 807-818, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[15] L. Piancastelli, L. Frizziero, G. Donnici. 2014. A highly constrained geometric problem: The inside-outhuman-based approach for the automotive vehicles design. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(6): 901-906, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[16] L. Frizziero, F. R. Curbastro. 2014. Innovative methodologies in mechanical design: QFD vs TRIZ to develop an innovative pressure control system. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(6): 966-970, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[17] L. Piancastelli, L. Frizziero. 2014. How to adopt innovative design in a sportscar factory. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(6): 859-870, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[18] L. Piancastelli, L. Frizziero, I. Rocchi: 2014. A low-cost, mass-producible, wheeled wind turbine for easy production of renewableenergy. Published by Pushpa Publishing House. Far East Journal of Electronics and Communications. ISSN: 0973-7006, 12(1): 19-37, Allahabad, India.

[19] L. Piancastelli, L. Frizziero, E. Morganti, A. Canaparo. 2012. Fuzzy control system for aircraft diesel engines edizioni ETS. International Journal of Heat and Technology. ISSN 0392-8764. 309(1): 131-135.

[20] L. Piancastelli, L. Frizziero, T. Bombardi. 2014. Bézier based shape parameterization in high speed mandrel design. International Journal of Heat and Technology. 32(1-2): 57-63.

[21] L. Frizziero. 2014. A coffee machine design project through innovative methods: QFD, value analysis and design for assembly. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(7): 1134-1139, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[22] E. Pezzuti, P.P. Valentini, L. Piancastelli, L. Frizziero. 2014. Development of a modular system for drilling aid for the installation of dental implants. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(9): 1527-1534, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[23] L. Piancastelli, L. Frizziero, G. Donnici. 2014. Study and optimization of an innovative CVT concept for bikes. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(8): 1289-1296, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[24] L. Piancastelli, L. Frizziero, G. Donnici. 2014. Learning by failures: The "Astura II" concept car design process. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608, 9(10): 2009-2015, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[25] L. Piancastelli, L. Frizziero. 2014. Turbocharging and turbocompounding optimization in automotive racing. Asian Research Publishing Network (ARPN). Journal of Engineering and Applied Sciences. ISSN 1819-6608. 9(11): 2192-2199, EBSCO Publishing, 10 Estes Street, P.O. Box 682, Ipswich, MA 01938, USA.

[26] L. Frizziero, I. Rocchi, G. Donnici, E. Pezzuti, 2015. Aircraft diesel engine turbocompound optimized. JP Journal of Heat and Mass Transfer. ISSN 0973-5763, DOI: 10.17654/JPHMTMay2015_133_150, Volume 11, Issue 2, 1 May 2015, Pages 133-150, Pushpa Publishing House, Vijaya Niwas, 198, Mumfordganj, Allahabad - 211 002, INDIA

[27] L. Frizziero, L. Piancastelli, 2015. Diesel ecu mapping optimization for aircraft and helicopter applications. JP Journal of Heat and Mass Transfer. ISSN 0973-5763, DOI: 10.17654/JPHMTMay2015_151_167, Volume 11, Issue 2, 1 May 2015, Pages 151-167, Pushpa Publishing House, Vijaya Niwas, 198, Mumfordganj, Allahabad - 211 002, INDIA.