UNIVERSIDADE ESTADUAL DE CAMPINAS
Faculdade de Engenharia Mecânica

JAIR LEOPOLDO LOAIZA BERNAL

Study of the operation of an internal combustion engine, fueled by indirect injection of ethanol and direct injection of water into the combustion chamber.

Estudo do funcionamento de um motor de combustão interna, alimentado por injeção indireta de etanol e injeção direta de água na câmara de combustão.

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When one's expectations are reduced to zero, one really appreciates everything one does have. *(Stephen Hawking, 1942-2018)*

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"With a little help from my friends"

"An expert is a person who has found out by his own painful experience all the mistakes that one can make in a very narrow field".

(Niels Bohr 1885-1962)

RESUMO

Na busca contínua pelo aumento da eficiência e redução do impacto ambiental, devido ao uso de motores de combustão interna (ICE), a injeção de água tem sido uma das estratégias mais utilizadas para atingir esses objetivos. Várias foram e ainda são as metodologias que utilizam a água como método de controle de temperatura e redução de emissões. Antes do uso de turbinas de jato e durante o uso de motores de pistão na aviação militar e comercial, a injeção de água e soluções de água e álcool foi implementada como uma estratégia para controlar a temperatura interna do cilindro durante a combustão. Isso permitiu o aumento das taxas de compressão com o consequente aumento de potência, principalmente em operações críticas como decolagens e manobras evasivas durante o combate. As conseqüências da aplicação desta técnica têm sido extensivamente investigadas em motores que utilizam combustíveis derivados do petróleo (gasolina e diesel). No entanto, em dispositivos que utilizam combustíveis alternativos, como o etanol ou outros biocombustíveis, existem poucas referências à pesquisa que utiliza técnicas de injeção de água nesses motores. A pesquisa aqui apresentada mostra os resultados da implementação utilizando simulação computacional de um modelo termodinâmico de duas zonas que integra a injeção de água líquida diretamente na câmara de combustão, em um motor que utiliza etanol como combustível. O modelo proposto interpreta a partir da termodinâmica o comportamento da água no interior do cilindro quando é injetado na forma líquida durante qualquer momento do ciclo. Até agora, esse tipo de análise foi realizado por meio de testes experimentais. Aqui a influência da água do ponto de vista teórico é estudada usando simulação. O modelo é validado comparando seus resultados com os da pesquisa experimental que implementa a mesma técnica de injeção de água proposta. A pesquisa mencionada usa um protótipo de motor que usa gasolina como combustível. Ao comparar alguns dos parâmetros operacionais, como a pressão no interior do cilindro, o consumo específico de combustível efetivo ou a taxa de liberação de calor durante a combustão, verifica-se que o modelo se comporta muito próximo do que foi relatado nos dados experimentais. Outras variáveis, como as emissões de NOx, apresentam tendências semelhantes entre o comportamento experimental e o simulado, apesar da grande variabilidade dos dados experimentais. Por fim, o modelo apresenta grande flexibilidade, pois pode ser utilizado para simular diferentes geometrias de motores, regimes de rotação e uso de combustíveis como gasolina, etanol, etanol hidratado e misturas destes em diferentes proporções.

Palavras-chave: Modelo termodinâmico, duas zonas, evaporação de gotículas de água, modelo de simulação, injeção de água, pressão, fração de massa queimada.

ABSTRACT

In the continuous search for the increase in efficiency and the reduction of environmental impact, due to the use of internal combustion engines (ICE), water injection has been one of the strategies frequently used to achieve these objectives. Several have been and still are the methodologies that use water as a method of temperature control and emission reduction. Before the use of jet turbines and during the use of piston engines in military and commercial aviation, the injection of water and water and alcohol solutions was implemented as a strategy to control the internal temperature of the cylinder during combustion. This allowed the increase of compression ratios with the consequent increase in power, especially in critical operations such as takeoff and evasive maneuvers during the fighting. The consequences of the application of this technique have been extensively investigated in engines that use fuels derived from petroleum (Gasoline and Diesel). However, in devices that use alternative fuels such as ethanol or other bio-fuels, there are few references to research that uses water injection techniques in these engines. The research presented here shows the results of the implementation using computational simulation of a thermodynamic model of two zones that integrates the injection of liquid water directly into the combustion chamber, in an engine that uses ethanol as fuel. The proposed model interprets from thermodynamics the behavior of the water inside the cylinder when it is injected in liquid form during any moment of the cycle. So far, this type of analysis has been carried out through experimental tests. Here the influence of water from the theoretical point of view is studied using simulation. The model is validated by comparing its results with those of experimental research that implements the same water injection technique that is proposed. The research mentioned uses a prototype engine that uses gasoline as fuel. When comparing some of the operating parameters, such as the pressure inside the cylinder, the specific fuel consumption at brake or the rate of heat release during combustion, it is found that the model behaves very closely to what was reported in the experimental data. Other variables such as NOx emissions present similar trends between experimental and simulated behavior, despite the great variability of the experimental data. Finally, the model presents great flexibility because it can be used to simulate different engine geometries, rotation regimes and the use of fuels such as gasoline, ethanol, hydrated ethanol and mixtures of these in different proportions.

Keywords: Model thermodynamics, two zones, simulation model, water droplet evaporation, water injection, pressure, mass fraction burned.

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LIST OF ABBREVIATIONS AND ACRONYMS

C = Carbon.

H = Hydrogen.

O = Oxygen.

N = Nitrogen.

Ar = Argon.

P = Pressure.

V = Volume.

m = Molar mass.

R = Universal constant of ideal gases.

T = Temperature.

U = Internal energy.

Q = Heat.

W = Work.

t = Time.

h = Entalpy.

c_p = Specific heat at constant pressure.

s = Specific entropy.

K = Equilibrium constant.

W, X, Y and Z = Molar fraction of atmospheric air components.

v = Specific volume.

b = burned.

u = unburned.

IVC = Intake Valve Close.

EVO = Exhaust Valve Open.

l = length of the rod.

A = Area.

Nu = Nusselt number.

Re = Reynolds number.

D_{AB} = Binary diffusivity of the spices A in a medium composed by the species B.

Y_A = Mass fraction of the species A (or B).

m_A = Mass flow of the species A (or B).

k = Thermal conductivity.

B_y = Conduction potential.

D = Diameter.

P_r = Prandtl number.

w = Water.

MW = Molar Weight.

L = length of rupture of the Levich jet.

TDC = Top Dead Center.

$BTDC$ = Before Top Dead Center.

$ATDC$ = After Top Dead Center.

$ABDC$ = After Bottom Dead Center.

$BBDC$ = Before Bottom Dead Center.

LIST OF SYMBOLS

θ = Crank angle.

ω = Rate of rotation of he engine.

ξ = Property.

ϕ = Equivalence ratio.

ε = Balance for the stoichiometric condition.

$\alpha, \beta, \gamma, \delta$ = Numbers of the atoms of each elements

ΔG° = Ground state of the Gibbs free energy.

ρ = Density.

λ = Wavelength.

CONTENTS

1 INTRODUCTION

The concept of water injection has often been associated with the history of the development of energy conversion processes through combustion. It is possible to find initial references on this association, in the patents of the first gas turbines, around 1791, where the injection of water appears as an auxiliary technique to control the temperature of the combustion gases and prevent damage in the later section of the turbines (HOPKINSON, 1913),(RICARDO, 1953). Towards the second half of the 19th century, coal and other solid fuels were progressively replaced by liquids, hence steam was introduced as a way to improve the atomization of these liquid fuels. However, there are few references to the development of double atomizers, for the steam and fuels used. In the first decade of the 20th century, steam was frequently used for atomization processes, due to the problems generated by the mechanical atomization systems used in large oil boilers and natural gas shortage (DRYER, 1977).

As well as boilers and turbines, the addition of water by injection techniques are also associated with the evolution of internal combustion engines (ICE). Bertrand Hopkinson used this concept around 1913 in the development of power plants that used water as a cooling agent (HOPKINSON, 1914). Hopkinson's idea was not new; however, at that time , he was the only one who managed to implement it in a practical, successful way.

Towards the First World War (1914), the use of water and ethanol-methanol-watermixtures played a leading role in increasing the operating efficiency of Otto engines (KOENIG; HEISER, 1943), however; antiknock agents, soluble in fuels, were discovered and developed by 1922. These investigations, together with the high costs and complexity of storage systems for water and water/alcohol mixtures, discouraged the use of these substances in the engines of the automobiles of that time.

A few years before the start of the Second World War and during its development, the research on supercharged engines for airplanes returned the interest in the injection of water and alcohol. (KOENIG; HEISER, 1943). Aircraft engines presented a severe tendency to detonate and overheat, which limited the uses of overfeeding and also the increase in compression ratios used until then for a high load operation. With the aspiration of water/alcohol emulsions, it helped to avoid the formation of ice and allow aircraft to reach the maximum power widely, during takeoffs and combat maneuvers (BELL, 1944). After the end of the war, water injection was implemented in turboprop engines and the first reactors for commercial aircraft. The company Pratt and Whitney offered the injection of water/alcohol as an option within its line of JT9D engines, used in passenger aircraft (DRYER, 1977).

Simultaneously with these developments and, as a consequence of the cost increase of automotive-grade fuel compatible with existing engines; great efforts were made to increase the